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METHODOLOGY FOR IDENTIFYING PROMISING RETROFIT INTEGRATED FOREST BIOREFINERY STRATEGIES – DESIGN DECISION MAKING UNDER UNCERTAINTY

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METHODOLOGY FOR IDENTIFYING PROMISING RETROFIT INTEGRATED FOREST BIOREFINERY STRATEGIES – DESIGN DECISION MAKING UNDER UNCERTAINTY

présentée par : HYTÖNEN Ville Eemeli

en vue de l'obtention du diplôme de : Philosophiae Doctor

a été dûment accepté par le jury d'examen constitué de :

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DEDICATION

To my family

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RÉSUMÉ

Le bioraffinage forestier est de plus en plus considéré comme une activité future prometteuse pour l'industrie forestière, et comme une approche plus respectueuse de l'environnement pour répondre aux besoins de la société en matière d'énergie, de produits chimiques et de matériaux. Le bioraffinage forestier est basé en partie sur les mêmes principes que ceux de l'industrie pétrochimique et cible pratiquement le même marché de produits. L'industrie forestière possède toutefois un avantage particulier comparativement à l'industrie chimique pour cette transformation : elle possède une expérience de longue date quant à la récolte et la transformation de matières premières biologiques. D'un autre côté, la compétitivité actuelle de l'industrie des pâtes et papiers (P&P) dans les pays traditionnels de production de P&P est compromise, et ce à cause du vieillissement de ses installations, des coûts d'énergie élevés, d'une réglementation stricte et des attentes élevées du public. Dans ce contexte, la prise de décision pour un investissement dans un procédé de bioraffinage devient un défi important et donne alors lieu à des pressions supplémentaires sur la conception de procédé et sur les processus de prise de décision visant à identifier les meilleures opportunités.

L'identification et la gestion des caractéristiques aux niveaux du procédé et de gestion stratégique, de même que les incertitudes reliées à l'implantation en rétro-installation du bioraffinage forestier est nécessaire pour la prise de décision concernant le choix d'investissements stratégiques. Présentement, de nombreuses méthodes sont appliquées à différentes étapes du cycle de gestion des affaires afin d'analyser l'impact des incertitudes. Au niveau du procédé, des méthodes et outils de conception de nouveaux procédés ou de procédés en rétro-installation sont appliqués pour analyser la rentabilité de projets stratégiques. Au niveau de l'entreprise ou de l'usine, des méthodes avancées de comptabilité sont utilisées pour analyser la performance au niveau des coûts des unités, et des rapports financiers sont effectués périodiquement pour caractériser la performance de l'entreprise. De plus, la prise de décision en groupe est de plus en plus utilisée pour la planification stratégique et les décisions d'investissement.

L'objectif de cette thèse est de développer une méthodologie qui améliore le lien entre la conception de procédé en rétro-installation, la comptabilité analytique et les activités de prise de décision reliées à l'investissement en capital, afin d'améliorer le processus de prise de décision

relié à l'investissement dans le bioraffinage forestier. Cette méthodologie est appliquée à une étude de cas considérant l'implantation en rétro-installation du bioraffinage dans une usine de P&P kraft.

La méthodologie consiste en la prise de décision par étapes successives, en commençant par une présélection d'alternatives de procédés basée sur des analyses technico-économique et de risques traditionnelles. La deuxième étape du processus décisionnel utilise un nouveau cadre combinant à la fois le processus de prise de décision d'investissements stratégiques, et la conception et la simulation de procédés par le biais d'un modèle économique basé les principes de comptabilité par activités.

Les modèles de coûts liés à la simulation de procédé sont d'une part en mesure de représenter avec précision les coûts de fabrication de tous les produits après l'implantation de procédés de bioraffinage. D'autre part, ces modèles sont capables de fournir des indicateurs financiers utiles pour l'évaluation des performances des projets stratégiques à court et à long terme. Par ailleurs, une analyse de risques utilisant une analyse stochastique multivariée peut être utilisée puisque toutes les mesures de performance sont explicitement quantifiées.

Les résultats de l'étude de cas montrent que l'analyse systématique des incertitudes externes peut fournir des informations essentielles sur les performances d'un projet dans le pire scénario, et ce même à l'étape de présélection des alternatives de procédé. Par ailleurs, l'analyse stochastique multivariée permet une évaluation plus objective des incertitudes au lieu d'utiliser des méthodes subjectives. De plus, les résultats d'analyse des alternatives de procédés retenues en utilisant le cadre élaboré quantifient clairement les impacts économiques des projets de rétro-installation. Ces impacts varient entre les alternatives, et ce à cause des différents potentiels d'intégration et des différentes contraintes du système de production existant. Dans le cas d'un processus normal de conception de procédé et d'affectation de capitaux, cette information sur les coûts ne serait disponible que pour les projets implantés et ce, après leur mise en service.

Le changement dans la compétitivité des coûts dans l'activité principale de l'entreprise peut être un facteur particulièrement important pour les producteurs de commodités papetières ayant des coûts de production élevés. En effet, lors d'un panel multicritères de décision (MCDM) où les différents calculs étaient basés sur ces données de coûts d'opération plus précises, l'intensité de différents critères de performance stratégiquement importants, tels que la performance du capital et la capacité de paiement pour les matières premières a été évaluée. Ce panel a montré que, même si certains critères de performance de projet à court terme ont été privilégiés, de bonnes performances au niveau des usines avaient également un rôle important dans le classement global. Ainsi, le classement final des alternatives obtenu lors de ce panel différait de celui obtenu lorsque seul le critère de rentabilité du projet était utilisé. De plus, les diverses importances relatives des critères de sélection de projet attribuées par les différents membres du personnel de l'entreprise ayant participé au panel ont démontré le caractère multiforme de ce problème décisionnel de choix d'investissements stratégiques. Par ailleurs, le fait d'utiliser une analyse de sensibilité lors du panel MCDM a permis d'illustrer l'impact des divergences de préférences des panélistes sur le classement des alternatives. En résumé, l'utilisation de cette méthodologie a d'abord permis de réduire un grand nombre d'alternatives de procédé pour l'usine de P&P à un premier ensemble d'alternatives potentielles, pour ensuite identifier une seule combinaison produit-procédé plus prometteuse. Cette méthodologie a donc été en mesure de lier systématiquement différentes analyses pour aider une entreprise manufacturière lors de la prise de décision pour le choix d'investissements.

Les travaux futurs comprennent l'élargissement de ce cadre méthodologique au processus de décision d'investissements stratégiques au niveau corporatif, afin d'améliorer davantage la gestion des actifs et la planification stratégique. Par ailleurs, une analyse des performances au niveau des opérations pourrait être incluse dans ce cadre afin de faire la conception de procédés de bioraffinage forestier flexibles bien adaptés à la stratégie d'entreprise.

ABSTRACT

Forest biorefinery is increasingly been considered as potential future business for traditional forest industry, and a more environmentally benign approach for supplying the demand of energy, chemicals and materials for the society. The forest biorefinery is partly based on the same principles, and it targets the same market sector, as traditional petro-chemical industry. However, the forest industry possesses a unique advantage over the chemical industry that is the long experience in bio-based feedstocks and their processing. The current pulp and paper (P&P) industry's competitiveness in traditional P&P countries due to ageing assets, high energy costs, strict regulations and high environmental expectations from the public, makes however the investment decision making challenging and thus gives rise to additional pressure on the design and decision making processes to help identifying the right opportunities.

Identification and management of the process and business level characteristics and uncertainties of retrofit forest biorefinery implementation is required in the strategic investment decision making. Currently, many methods are applied in different functions of the business life-cycle to analyse similar characteristics and impacts of uncertainties for varying purposes: at process level, retrofit and greenfield process design methods and tools are applied to investigate project feasibility and profitability for potential operational and strategic projects; at business or facility level, advanced cost accounting methods are used to analyse manufacturing system cost-performance, financial reporting is conducted to report business performance periodically, and group decision making is utilised in strategic planning and investment decision making.

The objective of this thesis is to develop a methodology to improve the link between retrofit process design, cost accounting and capital investment decision making activities to further enhance the investment decision making process for forest biorefinery. The methodology is applied in a case study considering retrofit biorefinery implementation into a kraft P&P mill.

The methodology consists of step-wise decision making starting with pre-screening of retrofit design alternatives based on traditional techno-economics and risk analysis, followed by an advanced decision making procedure. This second decision making step uses a novel framework combining process design and simulation through cost accounting models, based on activity-based costing principles, to strategic investment decision making process. The cost models linked to process simulation are able to accurately represent the manufacturing costs of all products after

retrofit biorefinery implementation, and on the other hand, these models are able to provide useful financial measures of short- and long-term performance of the projects and the facility for strategic investment decision making. Moreover, risk analysis using stochastic multivariate analysis can be utilized since all performance metrics are explicitly quantified.

Results of the case study application of the framework show, that systematic analysis of external uncertainties can provide critical information about the worst-case scenario project performance already in the project pre-screening stage. Moreover, multivariate stochastic analysis enables a more objective assessment of the uncertainties instead of using subjective scoring methods. Furthermore, the analysis results of the retained retrofit design alternatives using the developed framework clearly quantified the cost-impacts of the retrofit projects. These impacts vary between alternatives because of different integration potential and system constraints. In the case of normal process design and capital appropriation process, this cost information would be available only for the implemented project when it is operating. The change in the core business cost competitiveness can be especially important factor for the higher cost producers of commodity P&P products. Evaluation of the intensities of different strategically important performance criteria, such as capital performance or feedstock paying capability, based on this more accurate operating cost data showed that even though short-term project performance criteria were preferred, good facility-level performance based on the multi-criteria decision making (MCDM) panel had an important role in the overall ranking. The final ranking of the alternatives differed from that of using only a single criterion, project profitability. The attribute importance preferences of mill and company personnel from varying positions demonstrated the multi-faceted nature of this strategic investment decision making problem. Moreover, using sensitivity analysis in the MCDM was also able to illustrate the impact of the panellists' preference differences on the ranking. In summary, the complete methodology was able to narrow down a large amount of P&P mill retrofit alternatives first to a set of potential candidates and further to a most potential process-product combination, and thus was able to systematically link the different analysis activities in a manufacturing firm to aid investment decision making.

Future work includes the expansion of this framework into the strategic investment decision making at the corporate level, to further enhance the asset management and strategic planning. Furthermore, operations-performance analysis can be included in the framework to obtain flexible forest biorefinery designs with good strategic fit.

CONDENSÉ EN FRANÇAIS

Les industries traditionnelles de transformation chimique sont de nature intensives en termes de capital et de consommation d’énergie. Ceci provoque une pression importante sur l'industrie du bioraffinage qui est basée principalement sur les mêmes principes que cette première industrie. Cependant, comparée à l’époque du développement de l'industrie chimique, le développement du bioraffinage s’effectue à une époque où les coûts d'énergie sont beaucoup plus élevés, où la réglementation est plus stricte et où les attentes des consommateurs sont plus élevées. L’investissement dans le développement et l’implantation de grands projets de bioraffinage constitue alors un défi. En effet, la production de nouveaux produits de remplacement et de substitution entre en concurrence avec les produits dits traditionnels pour le même capital disponible. Les installations vieillissantes et l’augmentation des coûts pour remplacer les systèmes manufacturiers sont deux facteurs qui entravent le passage des projets de bioraffinerie, mais ceci offre également des opportunités.

Afin d'améliorer la faisabilité économique du bioraffinage, l’intégration du bioraffiange aux procédés existants tels que ceux des usines de pâtes et papiers ou des usines pétrochimiques pourrait fournir certains avantages: l'utilisation d’utilités centralisées, l’existence de systèmes d'approvisionnement en matières premières et de systèmes de distribution des produits, un savoir-faire correspondant, ainsi qu’une intégration d’énergie et de matière entre les procédés existants et nouveaux. Tous ces avantages offrent la possibilité de réduire le capital d'investissement requis de même que les coûts de production.

L’intégration d'une bioraffinerie dans une usine existante implique cependant des modifications au modèle d’affaire de l’usine, qui est à son tour doit être adaptée à la stratégie de l'entreprise. Le cas particulier de l’implantation du bioraffinage dans une usine de pâte et de papiers (P&P) transforme cette dernière en une bioraffinerie forestière (FBR). Cette direction stratégique, si appliquée adéquatement, pourrait aider l'industrie forestière à améliorer ses performances financières et son image. Par ailleurs, l'expertise existante de cette industrie en ce qui a trait à l’utilisation de biomasse comme matière première pourrait aider de façon significative le succès global de l'industrie de bioraffinage.

L’identification et la gestion de l'ensemble des caractéristiques importantes liées à l’implantation du bioraffinage, (les produits, procédés, matières premières et modèles d’affaires potentiels, de même que leurs incertitudes associées), est requise pour l'identification des opportunités d'investissement les plus prometteuses. Tel est l'objectif du processus de prise de décision pour le choix d'investissement pour une entreprise, dans laquelle les décisions concernant l'affectation du capital sont généralement basées sur un seul indicateur économique de performance du projet, tel que la valeur actuelle nette ou le retour sur investissement. Ces indicateurs sont le résultat d'une analyse de conception de plusieurs alternatives de procédé potentielles, menée habituellement par les ingénieurs de l'entreprise, des consultants ou des fournisseurs de technologies. Dans le cas de conception en rétro-installation, l'implication des actifs existants et du modèle d'affaire de l'entreprise est particulièrement important. Les diverses sources de données et différentes hypothèses utilisées pour les décisions d'investissement stratégiques peuvent conduire à des difficultés de comparaison de différentes alternatives d'investissement. L'information la plus précise sur les coûts pouvant être obtenue dans une usine est fournie par la comptabilité analytique. Celle-ci est basée sur des données historiques de performance du système de production et est aussi calculée à partir des données disponibles provenant des systèmes de gestion de l'information. Lors des dernières années, des méthodes comptables avancées ont été adoptées dans l'industrie de P&P et dans d'autres industries; ces méthodes utilisent des modèles de coût qui sont pilotés par les données. Cependant, cette capacité et ces coûts de produits ne sont généralement pas utilisés dans la prise de décision concernant le choix d'investissements, ou dans d'analyse technico-économique de conception de procédé.

L'objectif de cette recherche est de développer une méthodologie qui améliore le lien entre la conception de procédé en rétro-installation, la comptabilité analytique et les activités de prise de décision reliées à l'investissement stratégique afin de rendre le processus de prise de décision plus systématique. Cette méthodologie est appliquée à une étude de cas considérant l'implantation en rétro-installation du bioraffinage dans une usine de P&P kraft.

Cette méthodologie est particulièrement adaptée pour la phase d'affectation du capital dans un processus global de décision au niveau de l'entreprise (par exemple : à la phase de démonstration du concept ou à l'étape d'étude de préfaisabilité). Cette méthodologie comporte quatre étapes principales. Premièrement, une analyse de type larges blocs est effectuée pour ensuite éliminer les alternatives de procédé qui n'ont pas un bon potentiel économique ou qui comportent un risque trop important. Deuxièmement, des modèles de coûts basés sur les opérations sont développés et sont utilisés pour analyser les impacts des coûts sur des alternatives de procédés retenues. Troisièmement, une analyse des performances au niveau de l'usine est effectuée pour les alternatives retenues en utilisant les données des modèles de coûts et des critères d'évaluation pertinents. Finalement, une analyse multicritère de prise de décision basée sur un panel est utilisée pour obtenir les scénarios préférés d'affectation des capitaux.

Lors de la première étape, une analyse technico-économique traditionnelle a été utilisée pour la présélection des combinaisons matière première-procédé-produit et pour fournir des données de référence utilisées traditionnellement dans les méthodes d'affectation de capitaux. Les bilans de masse et d'énergie des procédés implantés en rétro-installation ont été établis en utilisant des modèles de procédé entrée-sortie. La rentabilité de projet et une mesure des risques du projet – la rentabilité inférieure limite (calculée en utilisant une analyse stochastique multivariée, l'analyse de Monte-Carlo) – ont été utilisées pour éliminer les alternatives de procédé les moins prometteuses. L'étape d'élimination a montré que l'analyse systématique des impacts des incertitudes externes conduit à des classements différents de projets de procédé comparativement à un classement basé uniquement sur la rentabilité attendue. Ainsi, les projets semblant être les plus prometteurs pourraient ne pas bien performer dans les conditions du pire scénario. Par ailleurs, une évaluation plus objective des incertitudes est obtenue au lieu d'une évaluation subjective qui est couramment appliquée durant cette phase de prise de décision.

Les alternatives retenues après cette présélection ont été analysés plus en détail en utilisant le cadre méthodologique élaboré pour le processus de prise de décision relié à l'affectation des capitaux. Ce cadre est composé des trois dernières étapes de la méthodologie globale.

Dans la deuxième étape, des modèles de simulation de procédé en régime permanent représentant les systèmes de fabrication en entier avec les contraintes du système existant ont été développés. Ces modèles montrent les impacts des projets de modernisation sur les conditions du procédé existant et les efficacités associées. Ceux-ci sont par la suite liés à la comptabilité analytique : des modèles de coûts basés sur les principes de la comptabilité par activités (ABC) sont développés pour déterminer les coûts de produits et le pro forma de flux de trésorerie. Lors de l'élaboration de ce cadre d'analyse des coûts, une analyse en trois étapes a été utilisée: 1) le développement des modèles de procédés et de coûts pour le cas de base, 2) la validation des modèles du cas de base en utilisant les données de l'usine, les états et rapports financiers de l'entreprise, et 3) le développement des modèles de procédé et de coûts pour toutes les autres alternatives de procédé.

Les modèles de coûts résultants convertissent les impacts sur le procédé en une meilleure compréhension des impacts sur les coûts, de même que le pro forma des flux de trésorerie reflétant la performance future de l'usine. Une analyse Monte-Carlo a été également incorporée dans le cadre d'évaluation des coûts pour analyser les risques de variation de flux de trésorerie. L'analyse des alternatives de conception retenues en utilisant le cadre d'évaluation de coûts élaboré quantifie clairement l'impact sur les coûts de ces projets de modernisation. Dans le cas d'un processus normal de conception de procédé et d'affectation de capitaux, cette information sur les coûts ne serait disponible que pour les projets implantés et ce, après leur mise en service. D'autre part, la compétitivité des coûts de produits de P&P est un facteur de performance à court terme important pour de nombreux producteurs. Sa quantification précise est par conséquent nécessaire pour l'analyse de projets de modernisation.

Dans la troisième étape, les critères de performance économique pertinents au contexte de prise de décision ont été sélectionnés. Ceci a été réalisé grâce à la compréhension des facteurs clé de performance dans cet environnement d'affaires. Quelques exemples de ces facteurs sont la structure de coûts des produits fabriqués, la compétitivité des coûts, les incertitudes spécifiques à l'environnement d'affaires comme les matières premières et les marchés, et les critères de performance du capital que les intervenants et investisseurs utilisent généralement lors de la prise de décision d'investissement. Une mesure appropriée a également été sélectionnée pour quantifier ces critères. Différentes mesures financières ont été utilisées et modifiées afin de bien refléter les critères choisis. Les stratégies d'investissement retenues sont ensuite évaluées en utilisant ces mesures financières calculées à partir des flux de trésorerie pro forma.

Dans la quatrième étape, une méthode multicritère de prise de décision basée sur un panel d'expert (MCDM) est appliquée afin d'obtenir les poids pour chacun des critères identifiés dans le but de mieux refléter les préférences de tous les intervenants. Lors de ce travail, une technique de compromis basé sur la théorie d'utilité multi-attributs a été utilisée. Lors de l'application de l'étude de cas à ce MCDM, où des critères de performance de projet à court terme ont été utilisés conjointement avec des critères de performance au niveau de l'usine, le classement final des alternatives obtenu a différé de celui obtenu lorsque seul le critère de rentabilité du projet était utilisé. De plus, selon l'analyse de sensibilité effectuée, ce classement final représenta adéquatement les préférences de chacun des membres du panel.

Les contributions les plus importantes de ce travail sont les suivantes :

- Une méthode qui utilise l'analyse Monte Carlo au stade de conception au niveau concept et préfaisabilité, pour l''incorporation et la gestion systématique des incertitudes externes à la conception lors du processus de prise de décision d'investissement
- L'étude systématique des implications de coûts dans les projets stratégiques de rétro-installation en liant la simulation de procédé à la modélisation avancée des coûts basée sur les principes de la comptabilité par activités (ABC). Cette représentation réaliste permet de mieux comprendre les changements dans les coûts et permet une meilleure prévision de la performance des activités futures
- L'accroissement de la cohérence entre les bilans de matière et d'énergie et l'analyse des coûts. Cette meilleure cohérence permet ainsi l'identification des variables de procédé et financières qui sont les plus affectées par les projets de modernisation, de même que la quantification de l'évolution de ces variables.
- Une représentation systématique des principaux critères d'affectation de capitaux et performance de l'entreprise par l'utilisation de modèles de coûts basés sur les opérations
- L'utilisation d'un ensemble de critères économiques et de risque qui reflète bien les besoins (au niveau de projet et au niveau stratégique), les conditions (les systèmes existants et les procédés en développement) et les facteurs de l'environnement d'affaires (érosion des prix pour l'activité principale de l'entreprise, la concurrence future pour la biomasse, les coûts d'énergie) lors de l'analyse des projets de rétro-installation. Ceci permet de mieux comprendre les opportunités de projets de modernisation dans le processus de prise de décision d'investissement.
- L'utilisation d'une méthode MCDM pour interpréter et pondérer plusieurs critères financiers de prise de décision. Ceci permet une décision rationnelle respectant à la fois les exigences des performances de projet et celles reliés à la vison de l'entreprise.

Les aspects suivants présentent quelques possibilités de recherche futures :

- La méthodologie développée d'aide à l'affectation de capitaux a été contrainte à la considération d'une seule usine de production. La méthodologie développée dans ce travail pourrait être adoptée pour de nombreuses unités de production d'une entreprise, afin d’être utilisée lors de la planification stratégique au niveau corporatif et lors de la prise de décision pour la gestion d'actifs.

- Le cadre d’évaluation de coûts pourrait être utilisé lors de l'analyse des impacts potentiels des décisions opérationnelles sur la performance financière de l'usine selon différents scénarios d'investissement. Ceci pourrait être réalisé par une analyse de coût marginale faisant varier les taux de production des produits, et par une analyse des coûts de production dans un système flexible de production.
- L’extension du modèle actuel pour examiner également des projets d'investissement opérationnels pourrait être d'un intérêt particulier pour les usines de P&P en raison de la complexité des processus et dans bien des cas, des équipements relativement anciens : l'évaluation proportionnée de toutes les dépenses en capital peut améliorer la gestion des actifs et donc l'efficacité globale du capital de la compagnie.
- En plus des incertitudes inhérentes aux modèles développés et des paramètres externes, l’incertitude liée aux paramètres de procédé pourrait être incluse dans l'analyse des risques des étapes de présélection des options et de MCDM.

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Variables

C	Cost of equipment; resource or intermediate resource cost; total production cost
CM	Contribution Margin
D	Driver
depr	Depreciation
FC	Fixed Costs
i	Cost index
M	Design capacity
P	Price
Prate	Production rate
Q	Mass flow
R	Revenue
t	Time
TC	Total Costs
U	Overall Utility
u	Utility
VC	Variable Costs
w	Weight
x	Attribute value in MCDM
z	Non-correlated variable in Taylor expansion function

Parameters

M	Number of MCDM criteria
N	Number of iterations in Monte-Carlo analysis

Subscripts and superscripts

α	Capacity exponent
i	Resource in cost model (variable cost type); attribute in MCDM
j	Intermediate resource in cost model

k	Resource in cost model (fixed cost type)
m	Product in cost model
ref	Reference for capital cost estimate
x	Capital spending type in cost model (strategic, replacement, development)

Abbreviations

ABC	Activity Based Costing
ADMT	Air-Dry Metric Ton
AHP	Analytic Hierarchy Process
BDT	Bone-Dry Ton
CDF	Cumulative Distribution Function
dep	Department
EBIT	Earnings before Interest and Taxes
EBITDA	Earnings before Interest, Taxes, Depreciation and Amortization
EtOH	Ethanol
FBC	Functional-Based Costing
FBR	Forest Biorefinery
FCF	Free Cash Flow
FSC	Full Standard Costing
FT	Fischer-Tropsch
FTL	Fischer-Tropsch Liquids
Geq	Gasoline Equivalent
HAC	Acetic Acid
HP	High Pressure (steam)
IRR	Internal Rate of Return
LCC	Life Cycle Costing
LP	Low Pressure (steam)
LPE	Law of Propagation of Error
MADM	Multi-Attribute Decision Making
MAUT	Multi-Attribute Utility Theory
MC	Monte-Carlo
MCDM	Multi-Criteria Decision Making

ML	Million litres
MMGPY	Million Gallons per Year
MODM	Multi-Objective Decision Making
MOO	Multi-Objective Optimisation
MP	Medium Pressure (steam)
M&E	Mass and Energy
NG	Natural Gas
NPV	Net Present Value
O&M	Operation and Maintenance
pdf	Probability Density Function
PSE	Process Systems Engineering
ROCE	Return on Capital Employed
ROI	Return on Investment
SG&A	Selling, General and Administrative Expenses
syngas	Synthesis Gas
SWOT	Strengths, Weaknesses, Opportunities, and Threats
t	Ton
VHP	Very High Pressure (steam)
VPP	Value Prior-to-Pulping

LIST OF APPENDICES

INTRODUCTION

1.1 Problem statement

Traditional chemical process industries are capital and energy intensive by nature. This leads to substantial pressure to biorefinery industry which to major extent is based on the same principles and business sector, but starting-up at time with significantly higher energy costs, stricter regulations and higher environmental expectations from the public. Investment into large development and implementation projects in such developing industrial sector is challenging, especially due to the fact that the manufacturing of the products to be replaced or substituted having increasing demand are competing from the same capital. Their ageing assets and ever increasing costs to replace the manufacturing systems both hinders the passing through of biorefinery projects but also offers opportunities.

In order to enhance the economic feasibility of biorefining, biorefinery integration into existing processes such as pulp and paper mills or petrochemical plants might provide some leverage: using centralized utility systems, existing raw material supply systems and knowledge, and product distribution channels, as well as suitable mass and energy integration between existing and new processes can offer substantially lower capital investment requirement and cost of production. Integration of a biorefinery into existing business implies however also modifications of the business model, that in turn has to be in line with the company strategy. The special case of implementing the biorefinery into a pulp and paper (P&P) mill transforms the P&P mill into a forest biorefinery (FBR). This strategic direction, when implemented properly, can aid the industry in improving their financial performance and image, moreover, the existing expertise in bio-based feedstocks and their chemistry can significantly benefit the overall success of the biorefinery industry.

Recognition and management of all the important characteristics of such biorefinery implementation, including the potential technological solutions, products, feedstocks and the business models, and the uncertainties in all these characteristics is required for identification of successful investment opportunities. This is the goal of the capital investment decision making process in a company, in which the capital appropriation decisions are often in the end based on only one economic indicator of project performance (such as net present value or return on investment). These indicators are the result of engineering design analysis of potential design alternatives, conducted by the company engineers, consultants or different technology providers. In retrofit case, the role of the existing asset and business is emphasized. Varying sources of data for the strategic investment decision making with different assumptions of this role can make it incorrect to compare the investment alternatives. The most accurate cost information in a manufacturing facility is provided by the cost accounting. This is based on past performance of the manufacturing system and calculated form the data available in different information management systems in place. During the last years, advanced accounting methods have been adopted in P&P and other industries; these methods are cost models that are driven by data. However, this capability and produced cost data is not used in investment decision making, or in process design techno-economic analysis.

A framework for retrofit design decision making that can utilize the capabilities and data existing in cost accounting and process design can potentially better serve the capital investment decision making process. The goal of this research is therefore to develop such a methodology to improve the link between retrofit process design, cost accounting and capital investment decision making activities, and further, make the investment decision making process more systematic. The framework should link process design and process simulation to the cost accounting and further to strategic investment decision making process: The process simulation models are detailed representations of the retrofitted manufacturing system with constraints of the existing system and therefore are capable of indicating the retrofit project impacts on the existing process conditions and efficiencies. The cost accounting is further able to convert these process-impacts into better understanding of cost-impacts, and into performance measures reflecting all the relevant attributes of the investment decision making. Using these attributes in a systematic multi-criteria decision making method, and utilising a decision making panel normally involved in such decision making process to give the attribute preferences (weights) can also better reflect the preferences of all stakeholders.

1.2 Objectives

Based on the problem statement, the main hypothesis of this work titled “Methodology for identifying promising retrofit integrated forest biorefinery strategies – design decision making under uncertainty” was formulated:

> ***The biorefinery strategy of a forestry company can be enhanced by better integration of process design with business lifecycle. Using advanced accounting, critical uncertainties can be systematically analyzed especially for the longer term in order to identify the advantages of transformative biorefinery projects and the core business investment projects***

This can be divided into three sub-hypotheses:

- *Accounting for uncertainties and future market scenarios in the early stage analysis of design options (Large Block Analysis) permits screening out strategies with large potential downside profitability*
- *A systematic Activity Based Costing (ABC) -like methodology permits an enhanced analysis of the potential impacts from biorefinery integration on the core product margins*
- *Long-term cash flows associated with different biorefinery strategies can provide the necessary knowledge for capital investment decision making*

The problem statement and the hypothesis call for the development of a systematic methodology to demonstrate the potential the proposed framework in investment decision making. This methodology is illustrated by case study at an existing kraft P&P mill considering the implementation of a biorefinery and involves the following objectives:

In order to address the hypotheses, the following objectives were set for the methodology. The main objective was:

> ***To develop an early stage design decision making methodology for retrofit biorefinery implementation into an existing forestry company that will better serve the capital investment decision making process***

The main objective was further divided into the following sub-objectives:

- *To develop an early stage design method for estimating profitability of possible forest biorefinery design options under uncertainty in order to be able to screen out less promising design options*
- *To develop an operations-driven cost modelling framework for calculating the manufacturing and marginal costs of production in an integrated forest biorefinery*

- *To develop a company-level evaluation method for defining interpretable financial and non-financial decision making measures for forest biorefinery investment decision making*

1.3 Thesis organization

This thesis is organized as follows: In chapter 2, the relevant literature is reviewed in order to identify the gaps in the body of knowledge. The next chapter presents the methodology and the case study to which the methodology is applied. Chapter 4 synthesizes the results obtained in the process of demonstrating the methodology. In chapter 5, general conclusions are given, followed by the contributions to knowledge and recommendations for future work presented in chapter 6.

In the Appendices A to D the articles that are published in, or submitted to peer-reviewed scientific journals are given. Other complementary papers are shown in Appendices E to H and additional background information in Appendices I to K.

CHAPTER 2 LITERATURE REVIEW

2.1 Current process design practices

2.1.1 Introduction

Process Design can be described to be "*the creative activity whereby we generate ideas and then translate them into equipment and process for producing new materials or for significantly upgrading the value of existing materials"* (Douglas 1988). This activity is carried out at different levels of detail and complexity, for example utilizing the Systems Engineering (SE) approach, defined by McGraw-Hill Dictionary of Engineering (1997) as *"the design of a complex interconnection system of many elements to maximise an agreed-upon measure of the system performance, taking into consideration all the elements related in any way to the system"*. When SE is applied to chemical-like processes it is called Process Systems Engineering (PSE).

Different PSE tools can be applied to realise these process design activities. In this chapter, the process design process is first introduced and then the main PSE methods to fulfil the objectives of the process design are reviewed.

2.1.2 Chemical Process Design

The strategy for healthy product-process development in the chemical industry can be either technology or market driven – new products are identified based on technology development or based on market needs and opportunities. In both cases, it is essential to match customer need and technical invention innovation. One solution to combine the strengths of both approaches is the innovation map, which connects the technology development and customer value-proposition. Another approach is the Stage-Gate™ Product and Technology development framework: The goal of Stage-Gate™ framework is to help transfer the good ideas to manufacturing through rigorous step-wise testing. The interconnection between the product and technology Stage-Gate™ frameworks depends on the approach (technology or market driven): the technology framework can either generate the product ideas or concurrently generate new strategies with the product framework. (Seider, Seader et al. 2009)

The Stage-Gate^{TM} framework resembles traditional process design development (Figure 2.1) which is conducted in stages to minimize the work and design costs by having the correct people and number of people working on the task. The stages of process design increase the level of detail in the design of the most promising options, while at the same time decreasing the uncertainty but also constraining more the system's cost reduction potential (Peters, Timmerhaus et al. 2003; Seider, Seader et al. 2004).

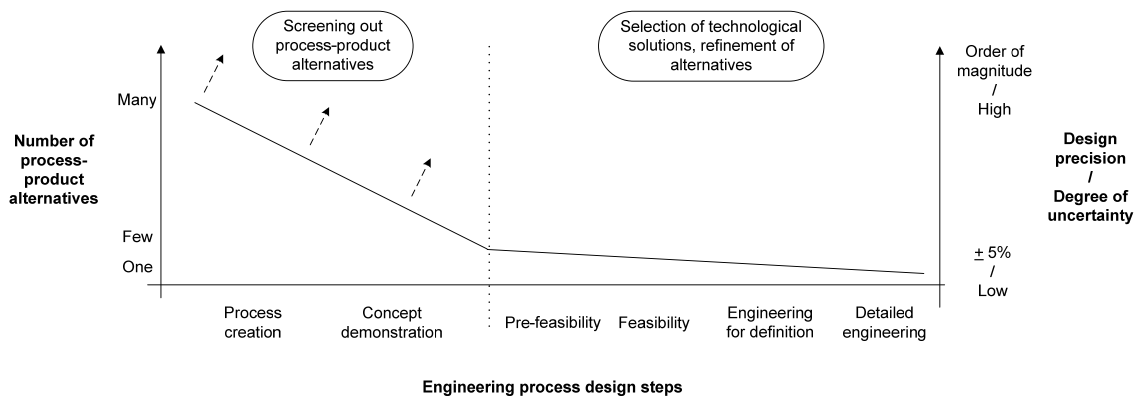


Figure 2.1 Engineering process design steps

Process design consists of flowsheet synthesis, technical and economic feasibility analysis and decision making tasks. Flowsheet synthesis starting at the conceptual design level with input-output models normally follows the principles of the heuristic hierarchical scheme proposed by Douglas (1988), or the mathematical programming based algorithmic generation scheme, explained for example by Peters, Timmerhaus et al. (2003). Several structured methods for flowsheet synthesis exist. The most well known representations of the feasibility and detailed-engineering level flowsheet synthesis are the onion model and the generation and optimisation of a superstructure of possible solutions (described for example by Smith (1995) and Gundersen (2000)). This normally includes a large amount of computations and is similar to algorithmic flowsheet generation. However, because the initial option generation step is done by a process engineer instead of a computer (by using heuristics), the superstructure approach can be considered as an enhanced hierarchical approach. Other representations of flowsheet synthesis are the water-fall model, V-model and spiral model. They describe the life-cycle of a process design project by dividing the above-mentioned stages in a different manner and introduce the validation of the design by comparison and iteration (Dimian 2003).

The same design principles and tools apply to greenfield and retrofit plant design. However, in retrofit process design the goals are different: improvement of existing operations in the form of debottlenecking, capacity increase, or technology upgrades are common targets for retrofit design, whereas in greenfield plant design a totally new production facility is the focus (Uerdingen, Fischer et al. 2003; Uerdingen, Fischer et al. 2005). On the other hand, this can also be the goal of retrofit design (e.g. retrofit implementation of a new product production line adjacent to the existing facility) when various design constraints need to be considered, including the process and business integration of a new feedstock-process-product combination into the existing systems.

2.1.3 Process modelling

The main tools of chemical process design are modelling and simulation. Based on available data and understanding of the phenomena taking place in the processes, mass and energy (M&E) balances of the considered designs can be modelled. The modelling can be executed with various techniques: in the early stages of design, spreadsheet models (often linear models) are used. When more fidelity and process parameter estimation is required, for example for better thermodynamic property estimation for heat balances, a steady state process simulation is used, and when dynamic behaviour of the process and equipment dimensioning are in focus, dynamic process simulation is used.

The outcome of modelling is used for several purposes: finding process bottlenecks from existing processes as a basis for cost estimation and environmental impact analysis of new and existing processes, or when doing detailed dimensioning of process equipment.

The level of detail needed, the design problem context and the strengths of different simulation tools should have a deciding role in the selection of the tool. For instance, Hytönen and Stuart (2009)used simple input-output models of possible integrated forest biorefinery options in a case study looking at biofuel production integrated into a kraft pulping mill. These linear spreadsheet models are easy to assemble and capable of providing the required level of detail for M&E balances for cost calculations in the conceptual process design phase in order to be able to screen out non-promising process options. At the pre-feasibility level process design, for example Mao, Genco et al. (2008) described a method for combining steady state process modelling of the overall biorefinery facility and detailed thermodynamic modelling of liquid-liquid separation system in order to have reliable mass and energy balances of the investigated process design. A similar combination has been used by Larson, Consonni et al. (2006) in estimating various thermochemical biofuel production routes integrated into kraft pulp mill. Thus, based on the need a suitable mix of tools should be selected for process modelling and simulation.

2.1.4 Techno-economic analysis

Economic performance is one of the main criteria in process design decision making. Depending on the purpose of the economic assessment and the design stage, the correct costing methods should be used. Two main costs are always estimated, operating and capital costs (e.g. (Dimian 2003)). Both use the modelled mass and energy balances and process conditions as basis.

2.1.4.1 Operating cost analysis

The variable operating costs (raw materials, energy, chemicals) are often estimated using monthly inventories, purchasing information and paid prices if these are available for another similar installation. For new concepts, variable operating costs need to be calculated from M&E balances, and fixed operating cost (labour, administration, maintenance, operating supplies, insurances, rents, other overheads, etc.) are estimated based on knowledge of the requirements to operate the system. Often, factors (fractions of capital investment costs or total operating costs) are used. Depreciation of the invested capital is estimated using the capital investment costs and planned depreciation schedule, and taxes are calculated as part of the cash flow analysis. These all are considered as operating costs. (Dimian 2003)

2.1.4.2 Investment cost analysis

Different design phases have standard capital cost estimation methods that are described in the engineering literature, see e.g. Dysert (2003), Peters, Timmerhaus et al. (2003) or Seider, Seader et al. (2009). Commonly used methods for capital investment cost estimation are different factorial methods: Based on a vendor quote for one unit/system, different factors (e.g. capacity, installation, material factors) and indices (Marshall & Swift cost index or Chemical Engineering Plant cost index) are used to estimate the cost of that unit/system in the new production facility at the time of installation. Equation 1 is suitable for both conceptual estimation at whole plant level and detailed single unit cost estimation at engineering for definition level of process design:

$$C = C_{ref}\left(\frac{M}{M_{ref}}\right)^{\alpha}\left(\frac{i}{i_{ref}}\right) \quad [1]$$

where C denotes the cost of new equipment, M the capacity of new equipment, α the capacity exponent, i the cost index and the subscript *ref* reference related values.

The single unit costs or department costs are then summed up to calculate the purchasing costs of equipment. This cost is multiplied with suitable factors to include installation, preparation and other plant building costs. Furthermore, a contingency cost is added to account for unexpected additional equipment to obtain the total capital investment costs of the project.

2.1.4.3 Profitability analysis

The main economic indicator in process design assessments is the profitability of the project. In the literature, the existing measures are divided into traditional indices, such as rate of return measures (return on investment (ROI), turnover ratio and payback time), and modern measures, such as net present value (NPV), discounted cash flow rate of return, or internal rate of return (IRR) (Sprague and Whittaker 1986; Dimian 2003). Other even simpler metrics are also used in comparisons in the literature, for example gross profit and capital intensity.

2.1.5 Process systems engineering methodologies for strategic investment decision making

Several retrofit process design methodologies have been proposed:

- Janssen (2007) proposed a generic retrofit process design methodology comprising of process and supply chain level assessment steps. The specific steps of this design methodology are: 1) design option generation based on available data, techno-economic study and environmental impact assessment (EIA) study; 2) operations driven cost modelling of the generated alternative designs; 3) Life cycle analysis and Supply Chain – level profitability analysis; 4) multi-criteria decision making (MCDM) process for selecting the preferred design option using economic, environmental and supply chain profitability as criteria. Thus, the methodology was targeting a sustainable capital spending decision.

- Uerdingen, Fisher et al. (2003; 2005) demonstrated the use of a novel methodology for systematic identification, development and evaluation of retrofit design alternatives. This methodology is capable of identifying potential projects with and without capital investment costs through decomposition of the existing process into component paths and assessing the variable costs (raw material, energy and waste) of individual component flows. The method was demonstrated using a case study in the fine chemicals industry (toluene production).
- Process integration investment decision making under uncertainty was studied by Svensson, Berntsson et al. (2009a; 2009b) targeting especially energy efficiency improving strategies. Pinch analysis, process simulation and optimisation and scenario planning was proposed to be utilized in consecutive steps.

Thus, methods for investment decision making at different design stages from generating alternatives to evaluating and choosing the most promising process design have been developed and demonstrated using case studies. However, these methods do not consider the cost-impacts and the company-level impacts of the retrofit projects for strategic investment decision making.

2.1.6 Biorefinery process design

2.1.6.1 Design strategies

A few overall approaches specifically for the biorefinery process design context have been proposed. These can be classified as product– and process-driven approaches.

Farmer (2005) illustrated the importance of product portfolio selection for a successful biorefinery strategy using case examples from the forest biorefinery. Market-wise counter-cyclic products in the portfolio can be used to hedge against market volatility, and flexibility to change the production volumes can absorb part of the potential impacts of market penetration of emerging markets.

Wising and Stuart (2006) proposed a framework to advance this idea of product portfolio design by combining it with process design using process systems engineering and process integration tools to conduct preliminary engineering (i.e. data reconciliation, process simulation, Life Cycle Assessment, Pinch-analysis, Supply chain management, multi-criteria decision making). This approach is designated to serve strategic planning of forest industrial companies. Furthermore, Janssen, Chambost et al. (2008) and Thorp (2005) have proposed different phased approaches for implementing the forest biorefinery, considering the current strengths and constraints of the forest industry and full utilization of the existing assets at the same time focusing on the most suitable product portfolio for the mill and the company.

Sammons Jr., Yuan et al. (2008) proposed an approach for biorefinery process and product design in general. A combination of several tools (process simulation, interactive process and molecular design, optimisation, environmental impact analysis) is used to solve the difficult selection problem. The idea behind this method differs from the above presented strategies: the framework of Wising and Stuart is market driven, whereas the method proposed by Sammons et al. is technology driven (superstructure optimisation defines the end-products). Second difference is in the selection method: the first approach is capable of considering multiple objectives simultaneously with MCDM, whereas the latter methodology relies on stepwise decision making.

2.1.6.2 Forest biorefinery concepts

Various forest biorefinery process strategies and process designs have been proposed. Traditionally the biorefinery processes are categorized into biochemical and thermo-chemical pathway processes. For forest biorefinery, another useful classification is the division into adjacent and tightly integrated biorefineries: adjacent processes utilize the existing systems maximally but do not interfere with the pulp and papermaking material balances, tightly integrated biorefinery processes are also exchanging material with the P&P processes. Examples of the adjacent forest biorefineries are production of pellets or transportation biofuels from forest or agricultural based feedstocks; examples of the latter group are hemicellulose extraction from wood chips prior-to-pulping, lignin separation from black liquor, or black liquor gasification for chemical recovery, and energy and bio-product production. Specific solutions proposed for tightly integrated forest biorefineries include near-neutral green liquor extraction of hemicelluloses for ethanol and biochemicals production (van Heiningen 2006; Mao, Genco et al. 2008; van Heiningen 2010), hot-water hemicellulose extraction to produce biofuels and bio-chemicals (Amidon, Wood et al. 2008; Amidon and Liu 2009), partial dilute-acid pre-hydrolysis of loblolly pine for hemicellulose extraction prior-to-cooking for ethanol production (Frederick, Lien et al. 2008), black liquor gasification combined cycle system for Tomlinson recovery boiler replacement and simultaneously biofuels production (Larson, Consonni et al. 2008; Larson, Consonni et al. 2009), or carbon dioxide and sulphuric acid utilization for lignin precipitation and filtration from black liquor (Öhman, Wallmo et al. 2007). The major difference between the hemicellulose extraction –based solutions lies in the used chemistry (green liquor, water only or sulphuric acid respectively) and therefore the obtained products differ. In addition, the separation strategies for by-products are different: liquid-liquid separation for acetic acid separation, membranes for organic acid separation, or no separation of other products respectively. Specific solutions for adjacent strategies include for example steam-reforming (Connor 2006) or high temperature gasification (Larson, Consonni et al. 2008; Larson, Consonni et al. 2009) of bark and forest biomass followed by Fischer-Tropsch liquids synthesis. Moreover, adjacent biorefinery processes could also include first-generation biofuels production (Hytönen and Stuart 2009; Hytönen and Stuart 2010).

These FBR concepts represent the first phases of overall implementation strategies, which consider the current strengths and constraints of the forest industry and aim at full utilization of the existing assets (Thorp 2005; Janssen, Chambost et al. 2008). These integrated bio-energy processes (energy in the form of fuels, heat and electricity) are expected to lower the manufacturing costs of P&P products and diversify the product portfolio. The focus in the forest biorefinery process design has been on the second aspect and the cost-impacts have not been addressed.

A special design strategy for forest biorefinery was proposed by Phillips, Jameel et al. (2010) to exploit the equipment of a shut-down P&P mill in biofuel production process, extending the useful lifetime of this asset and decreasing significantly the initial capital investment costs of the biorefinery facility.

2.2 Manufacturing cost analysis

2.2.1 Management cost analysis

The survey of Farragher et al. (1999) on 379 U.S. based companies' practices in the capital investment decision making process implies that relatively detailed operating costs evaluation is used in investment project analysis. This is done to arrive at good forecasts of annual operating cash returns, changes in working capital and their residual cash flows. Similar implications arise from other capital budgeting research (e.g. Hogaboam and Shook (2004)). Furthermore, a key requirement arising from the industrial context is a better understanding of the impacts of possible changes in the business environment on these forecasts (and capability of retrofitted facilities to perform under the changing conditions).

Costing in general has a significant role in operational decision making. Product pricing and add/drop decisions are often done partly based on costs of production. In a study by Paul and Weaver (2002), relevant costs and appropriate measures for this particular decision making context were examined. Their survey showed that several methods are often used in parallel: full standard costing, direct standard costing, incremental cost analysis or different mark-up evaluation. Although short-term decisions should be based on a contribution margin or variable costs and long-term decisions based on full standard costing (FSC), many of the survey recipients are not following this norm of microeconomics (fixed cost of capacity is a sunk cost and non-relevant for operation decision making). Rather, due to various management practices even opposite methods are used to guide decision making. Based on Paul and Weaver, it is critical to better understand the relevant costs for a particular product decision (add/drop, make/buy, volume- or order-related) and keep in mind the possible long-term impacts of short-term decisions such as influence of gradual increase/decrease of production of a product on support costs or changes in non-manufacturing costs. Also, they conclude that the limitations of full standard costing or total product costs as decision making basis should be better recognized.

Panzar and Willig (1977) defined the concept of *economies of scope*, a reason for companies to produce multiple products in one facility/company and therefore benefit from the co-utilization of physical assets and knowledge in production of all the products. Even though not applicable to all cases (e.g. to the case of significantly differing products), the concept helps in understanding what costing methods best apply in an operations decision making context.

Kee (2008) further concretized the differences between marginal and full costing methods under the assumption of economies of scope conditions for pricing, product mix and capacity related decisions, and Haka, Jacobs et al. (2002) examined the impact of allocation of fixed costs, or different costing principles, in the same decision making context under oligopoly market conditions.

Most applied cost analysis practices in investment decision making and operations decision making are the different product costing methods and marginal costing. Furthermore, in all costing, allocation plays an important role. These aspects are reviewed in the following sub-sections, followed by a review of the use of these costing methods in process design context.

2.2.1.1 Product costing

Traditional product costing methods are used commonly in all industries mainly for reporting financial accounts at the end of a reporting period. They are based on assigning total costs incurred during the period (measured from changes in raw material inventory levels and purchased raw materials through the period of analysis) using plant-wide blanket rates and average production rates to products. Depending on the production system (single product or multi-product) and allocation and assignment rate bases, this traditional method can lead to significantly differing costs from the "true" product costs.

An enhanced traditional costing method is functional-based costing (FBC). It adds one level of detail to the facility level cost hierarchy of traditional costing: the costs are allocated and assigned at unit-level (a unit is defined as the production line of a product, for a single-product facility the facility is the unit) and then aggregated into the facility level for reporting and analysis. The allocation rates, or drivers, are measured with production rates, direct labour hours or machine hours. Hence, individual facility units or departments first consume cost pools and these units or departments are consumed by products, instead of assigning all costs directly to end products. The allocation of all costs with unit-level drivers (including non-unit related overhead costs such as setup costs or grade change costs or seasonal maintenance or corporate overheads) can distort the product costs if non-unit-level relative overhead costs are a significant part of the total overhead costs and if different products produced in a unit have a different overhead activity demand. In addition, overhead cost absorption systems might be needed in order to transfer period costs to other products or periods.

In activity-based costing (ABC) also the non-unit-level drivers are defined in addition to the FBC cost-hierarchy, and therefore it should lead to product costs that are closer to the true costs. Different opinions about the accuracy of these methods exist and no absolute measure of the correctness of product costs based on any costing method is available. Cooper describes ABC as a more correct means for product costing in today's industry setting (large companies) where expenses covering marketing, distribution and support are a significantly increased proportion of the total costs compared to traditional direct labour and material costs. Thus, facility and corporate overheads have increased importance and the costing method should be able to properly allocate these costs (Cooper and Kaplan 1988; Cooper and Kaplan 1991). On the other hand, when multiple products are produced simultaneously, ABC can enhance the cost estimates. For example, Wang, Shan et al. (2008) report the implementation experiences of ABC in the Chinese refinery industry to better cost the intermediate products in addition to the final products. A theoretical proof of cost accuracy has also been studied by Charles and Hansen (2008) who applied game-theory concepts to develop measures for accuracy of FBC and ABC in product costing. They conclude that theoretically ABC yields product costs relatively closer to the true costs if there is sufficient product diversity (the product's consumption of the individual cost pools are sufficiently different, thus the individual unit-level drivers of FBC differ enough from the activity drivers of ABC).

The major difference between the traditional approach and the ABC approach are also illustrated in Figure 2.2. (modified from Emblemsvåg and Bras (2001))

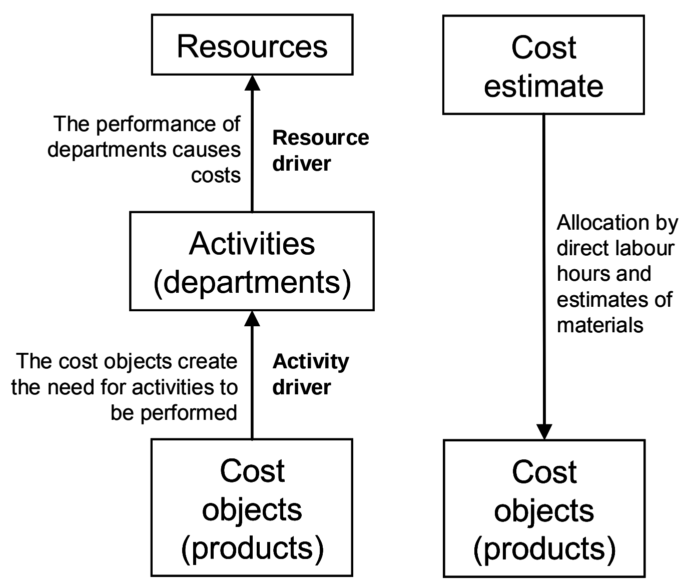


Figure 2.2 Volume-based costing vs. ABC costing

Brierley, Cowton et al. (2006) investigated the product costing practices in discrete manufacturing and continuous process industries using a survey. ABC was not found to be a major costing method in these industries, moreover, there does not seem to be any significant difference between ABC practices of these two types of industry. Differences exist in the bases for activity and resource driver definitions: continuous process industries use production rate and time as driver more often instead of direct labour that is used in discrete manufacturing.

Based on the discussed benefits of using ABC and the context of this work (FBR – multi-product and continuous process system), using ABC as accounting method should yield better cost information than traditional accounting methods and help in all cost-based decisions such as pricing, product mix and make or buy decisions. Methodologies have been proposed for the use of ABC in operational decision making, e.g. by Greenwood and Reeve (1992): They recognized the pooling of costs based on an activity driver as a limitation of standard ABC. If this was done based on an actual process, this would significantly enhance the management's understanding of *process costs* and lead to a better capability to continuously improve processes. Their framework was designed to overcome this limitation through the use of an appropriate activity architecture, and product attribute and process-based driver definitions.

2.2.1.2 Marginal costing

An example of relevant cost analysis is marginal costing. Almost all continuous production systems are somewhat volume-flexible which enables short-term changes in production volume from design capacity to supply the changing demand of products or to react to attractive market prices. The relevant costs in this case are variable costs and an often used measure is the marginal cost of product m or the cost of one additional unit of product m more produced:

$$C_m^{marginal} = \frac{dTC_m}{dQ_m} = \frac{d\left(FC_m + VC_m\right)}{dQ_m} = \frac{dVC_m}{dQ_m} \qquad [2]$$

where Q_m is the flow of product m, TC_m, FC_m and VC_m are the total, fixed and variable costs of producing product m.

Another measure is the contribution margin CM:

$$\begin{aligned} CM_m &= R_m - VC_m \\ CM &= \sum_m CM_m \end{aligned} \qquad [3]$$

where R_m is the unit revenue (or price) of product m. CM shows how an increase in production translates to profits, and thus is able simultaneously to consider marginal costs and marginal revenues. This can also be aggregated into one contribution margin mark-up to measure the overall operating leverage of the facility and it can be measured as the percentage of either revenue or variable costs or as absolute value as in equation 3.

When using equations 2 and 3 it is important to include in the variable costs possible changes in other products' variable costs, as those are relevant costs to the production rate change. Furthermore, if the operating point is expected to differ from the design point for a longer period of time, also fixed costs should be included in the decision making and thus full costing is preferred.

Kloock and Schiller (1997) investigated the use of marginal costs in short- and long-term decision making to compare it with ABC as a decision making basis. By definition, marginal costs are assigned by the *cause and effect* principle, whereas in ABC assignment is based on *demand*. This leads to the fact that in ABC the short-term fixed costs are also assigned to products (services etc. are required in order to produce the product) but in marginal costing since the additional products produced do not cause change in services etc., their cause (fixed cost) is not relevant. Based on the analysis of both methods for product pricing, the same solution is obtained, thus no difference in the pricing decision should occur if ABC is correctly implemented.

2.2.2 Cost allocation and assignment

Overhead cost allocation, among other cost allocation aspects including joint cost allocation and activity based costing, have gained increased interest in the management accounting literature (e.g. Hesford et al. (2007) studied management accounting literature between 1981 and 2000). Major reasons for this are the need to be able to better respond to changes in the market place and to optimize the manufacturing system for the chosen product mix. Haka, Jacobs et al. (2002) studied the impact of overhead cost allocation on product mix decision making when acting on oligopoly markets. They concluded that using full costs in decision making rather than variable costs (commonly used in operational product mix decision making) gives a response to other sellers' reactions that is closer to optimal. Thus, proper overhead cost allocation reveals the opportunity costs of the alternative use of a fixed asset and can steer to an optimized product mix.

In ABC, different overhead cost allocation bases define the final products' shares of the total overhead costs. These bases are, depending on the overhead cost type, either overall blanket rates or fixed at the departmental level to headcount, sales or square footage.

Assignment of joint costs of one activity to several products (such as process steam and electricity from steam turbines, bark and wood from debarking, or pulp and weak black liquor from cooking and washing) also requires bases. For the case of steam pricing, several bases have been used: enthalpy or entropy difference between different pressure level steams, electricity generation potential of the expansion of steam from pressure level to another, or exergy (Bejan, Tsatsaronis et al. 1996; Smith and Varbanov 2005). For material flows, a by-product stream value is normally fixed to a relevant value based on the replacement value of that stream in the system (e.g. bark is assigned a heat content adjusted value of purchased fuel) or to a zero value. Moreover, these fixed values are often kept constant in retrofit analysis regardless of the changes in costs of producing these by-products.

2.2.3 Advanced manufacturing cost analysis in process design

Cost analysis in process design traditionally focuses on capital investment cost evaluation and not on operating and maintenance (O&M) cost estimation. However, some overall methodologies including advanced O&M cost analysis methods, and accounting methods, in continuous process industries have been proposed:

- Sadhukhan et al. (2007; 2008) developed a novel process synthesis methodology for retrofit process design based on value analysis. A superstructure is formed from all retrofit alternatives and mathematical programming is used to find out the optimal states or operating policies of the subsystems of the master problem, or one path in the superstructure. For cost evaluation, these optimal states (with steady-state simulation filling the missing data when subsystems are combined) are used. Every process network is decomposed to a directed graph in which the cost of production and value of processing are evaluated for every complete stream. The difference between a process element input stream cost of production and output stream value of processing measures the economic margin of that element and when these element margins are aggregated they form the total margin of the facility. Thus, the method approaches this process element from both raw material and end product directions simultaneously in order to arrive at the needed values and costs of all streams. Cost allocation between multiple outputs of a process element is not considered explicitly, all products of an element are given the same cost of production. The methodology is illustrated using the retrofit integration of an oil upgrading system into a refinery and implementation of arabinoxylan co-production in an ethanol plant.

- Janssen et al. (2007; 2008) introduced the utilization of ABC-like cost modelling in a single-product and multi-feedstock system retrofit design problem. The industrial context was increased deinked pulp production and cogeneration at an integrated newsprint mill. The cost model resource and activity driver performances were linked to the mill information management system when appropriate, and production functions were used to estimate drivers that needed to be calculated from available data (e.g. new processes introduced by the retrofit design scenarios). In joint cost assignment, fixing by-product cost flows was used to get the main product cost flow between activities and overhead costs were allocated to different activities using fixed rates. This cost information was further used in net present value analysis of the retrofit project alternatives and in a supply chain model to optimize supply chain profits.

Marginal costing has also been presented as a costing method for process design:

- Hui (2000) introduced a linear programming method simultaneously evaluating three marginal value metrics (marginal profit and marginal cost as feed or as product). The method was illustrated using two example processes and interpreting the physical meaning of the metrics. It was shown how these metrics give valuable indications about process bottlenecks, deficits and surplus in a design and thus can guide retrofit design decision making. Additionally, it was discussed that the knowledge of all intermediate stream marginal value metrics can help to decide whether some intermediate streams should be purchased or produced or sold without further processing them.

- Similarly Li and Hui (2007) applied the above described marginal value analysis to a refinery planning context and extended the estimated marginal impacts from the initial solution point (marginal value analysis gives an indication of the values only at the solution point) to a wider range of points in the solution space by using sensitivity analysis and parametric programming. This, as the work above of Hui, is a suitable method for operational decision making and debottlenecking for retrofit project identification purposes.

- Janssen, Naliwajka et al. (2008) also illustrated the marginal costs of energy (steam and electricity) and marginal impacts of production rate change on project profitability using the ABC costing method described above. The results indicate that system constraints govern in that specific context and that design capacity was the most suitable with regards to all marginal performance measures.
- Varbanov, Perry et al. (2004) and Smith and Varbanov (2005) utilise marginal cost analysis in a top-level analysis methodology (developed by Makwana, Smith et al. (1998)). This method calculates the true cost of utilities using joint cost assignment rule and it is targeted at the identification of potential retrofit energy projects.

Sandström (1999b; 1999a) investigated the fit between management costing and engineering design, focusing on ABC and how the ABC system should be constructed to be used in product costing in process design. The survey conducted with design engineers indicated that costs structured using ABC and activity chains are informative and useful. ABC is concluded to be well suited for the early stages of design, whereas the needs in later design phases are not best met by using an ABC method. Rather, specific formulations of costs should be utilized.

Although advanced costing has been proposed to be used in process design and in retrofit design context, the utilization of the full potential of advanced costing has not been presented. Thus, the major advantage of ABC and some other advanced costing methods (capability for systematic cost assignment to all products) has not been presented in design context. Moreover, the cost analysis development has focused on providing more transparency in cost information, however, this data is been aggregated to a profitability measure and has not been used explicitly in design decision making.

2.3 Risk analysis in process design techno-economic assessment

In process design, several sources of uncertainty exist. Based on Pistikopoulos (1995), the sources of uncertainty in design can be classified based on their nature to be a) model-inherent, b) process-inherent, c) external and d) discrete. Most commonly considered uncertainties in design analysis are external uncertainties (category c). The external uncertainty analysis aims at capturing the uncertainties at the outset of the design project, namely the uncertainties at company, industry or general environment levels in order to be able to better manage these uncertainties (Miller and Waller 2003). It can include also behavioural uncertainties related to management actions, however these are normally not included in design analysis.

If risk analysis is not conducted in design for capital project evaluation, the "implicit assumption is that all projects considered are of equal risk and that risk is the same as the risk for firm as a whole", (Chadwell-Hatfield, Goitein et al. 1996). Thus, especially in the case of retrofit capital appropriation when there are both new and traditional technology alternatives, it is imperative to analyse risks. Normally the new retrofit alternatives have higher risks than traditional alternatives and therefore assuming the risk level in all project to be the same as for the firm as a whole can be wrong.

General risk analysis in process design follows four main steps: 1) Identification of sources of uncertainty, 2) quantification of uncertainties, 3) formulation of uncertainty for risk analysis, and 4) quantification of risk. In techno-economic analysis the risk analysis method should be selected depending on the process design stage (the goal of the design analysis), the sources of uncertainty and information availability. Several qualitative or quantitative methods for incorporating uncertainty into the techno-economic analysis exist.

2.3.1 Qualitative analysis methods

Qualitative risk analysis is best suited for investment strategy or project risk evaluation at the early stages of the decision making process. Thus, it can be considered a prerequisite for actual process design and synthesis activities and more detailed quantitative risk analysis. SWOT analysis (project Strengths, Weaknesses, Opportunities, and Threats -evaluation) is one qualitative method used in strategic planning (English, Gordon et al. 2006). Under generic and qualitatively defined conditions, each uncertain aspect is verbally (often subjectively) "quantified" to arrive at an overall benefit-disadvantage description of each considered scenario.

2.3.2 Quantitative analysis methods

Quantitative risk analysis uses different numeric scales to categorize the input parameters or the system's behaviour under different conditions. It can be further divided into deterministic and stochastic methods. These methods can be applied either as such or incorporated into other design methods such as optimisation under uncertainty

2.3.2.1 Deterministic analysis methods

Deterministic risk analysis includes two types of methods: I) methods where the uncertain input parameters are given a range of possible values with the same probability of occurrence. The quantified uncertainties are then propagated through the analysis model to the end results; and II) methods where some aspect of the system is considered uncertain and it can be categorized subjectively using an ordinal or verbal scale and be represented as a result. Usually, the methods either arbitrarily or based on knowledge of the context and heuristics of the phenomena behind the uncertain parameters quantify the uncertainty and fix the parameters to some values to form a set of scenarios for analysis.

Examples of the type I methods include interval analysis or sensitivity analysis, where ranges (minimum and maximum values) are used for uncertain model parameters. These are especially useful methods if no information of likelihood or probability of parameter values is available. Solving the problem with boundary values of all uncertain model parameters represents the absolutely worst/best case scenario (Goh, Booker et al. 2005). In process design sensitivity analysis, uncertain parameters are considered one at a time keeping other parameters at their expected values (base case values) to obtain the sensitivity of the system to the parameter varied. This helps identifying the *risky* system parameters: parameters that have substantial impact on the analysis results if they vary over their quantified range of possible values.

Another deterministic method, scenario planning or analysis, uses the same principles as interval analysis: *"By iterative and interactive group decision process, including discussions among managers and other stakeholders, all different likely future scenarios, thus the likely values of risky parameters, will be examined leading to few most plausible and internally consistent future scenarios"* (Schoemaker 1995). It is mainly intended for strategic planning but it also captures the main idea of risk mitigation and analysis in process design. This approach could be used in process design to generate input value scenarios also without utilizing the formal procedure proposed by Schoemaker. An expert group (process design group) can be utilized to generate these scenarios. This approach has the same weakness as interval analysis – the probability of planned scenarios is not achieved systematically.

Type II methods include different scoring methods, which, using a subjective understanding of the system, quantify the magnitude of the uncertainty in some behaviour. An ordinal scale is used for quantification of the uncertainty score that is either used as such as a decision making criterion, or converted to the units of a used performance measure and discounted from its value. Discounting can be done case-by-case in order to be able to better compare significantly different scenarios or process design alternatives. For example, the performance of a design alternative with the main product having fully established markets is not discounted, whereas if the main product does not have existing markets, or the market is difficult to enter, the performance measure of that design alternative is discounted based on a developed scale. Thus, the perception of the market conditions is used to evaluate the potential impacts of that market condition on profitability. Similarly, other design aspects can be addressed.

Scoring methods can be useful in multi-criteria decision making in early stage design in order to avoid complex models and time consuming modelling and simulation.

2.3.2.2 Stochastic analysis methods

Stochastic risk analysis is based on the probability distributions of uncertain model parameters. Selecting random values from these distributions, a large amount of scenarios (input parameter combinations = scenarios) are generated. In the analysis of all these scenarios all uncertainties are propagated to the results forming their probability distributions, e.g. the probability distribution of profitability of the investment project. An important step in stochastic analysis is to identify the correlations between uncertain parameters.

The most well known stochastic analysis method is Monte-Carlo (MC) analysis in which the solver randomly selects values from the uncertain variable probability distributions and calculates the outcome. By repeating this many times (often 10^5-10^7 times), many of the possible parameter combinations (scenarios) are calculated. Because the randomly selected input values are based on their probability, the result is correctly distributed.

This random sampling can be further enhanced, for example Latin Hypercube Sampling can be applied (comparison of the performance of different sampling methods is reviewed e.g. by Wang, Diwekar et al. (2004)).

The interpretation of the results of stochastic modelling involves always two aspects, the expected value and the variance or statistical dispersion. Presenting the result distribution as Cumulative Distribution Functions (CDF) combines these two aspects. Mathematical methods for comparing resulting CDFs have been developed. From these methods Graves and Ringuest (2009) proposed two, almost stochastic dominance and mean-Gini methods, to be most suitable for comparing several options.

Another method for estimating the uncertainty in outcomes is based on the definition of variance and its propagation: variance is the second central moment of a real valued random variable which can be estimated using a Taylor expansion of the function describing the outcome y as a function of its variables z, $y = f(z)$. This expansion is often truncated after the second order term and in the case of non-correlated variables z, the covariance between variables can be omitted leading to less complex formula for the outcome variance. This method, law of propagation of error (LPE), is commonly used in analysis of the impacts of measurement uncertainty on results reported with a metric calculated from the measurements (e.g. variance of resistance is calculated from measured voltage and electric current) (Taylor 1997). It is not commonly applied in the process design context. Xiao and Vien (2003) compared this method with Monte-Carlo analysis in mineral processing system modelling and concluded that even though LPE can be applied in this context, Monte-Carlo analysis leads to more informative and accurate results. The main reason is that LPE is only able to give correct answers for linear functions, whereas Monte-Carlo analysis can also handle non-linear and complex system models.

The limitations of this LPE method (inaccuracy when complex, non-linear systems are analysed) can be justified in cases where the calculation time is an important factor: evaluation of one equation is fast compared to 10^5-10^7 iterations often conducted in Monte-Carlo analysis. Moreover, if the actual probability density function is not the objective of the uncertainty analysis and the statistical moment (variance or standard deviation calculated from variance) of the outcome is sufficient, LPE could be applied.

2.3.2.3 Optimisation-based analysis methods

Finite number bounds or fixed parameter values (scenarios) can be used to describe the uncertainties of the system, and thus deterministic approximations are used to define possible scenarios among which the optimal solution is looked for. These possible model parameter combinations (scenarios) can also be given a probability value, for example using expert opinions. This probability of the occurrence of the scenarios is then also the probability of the corresponding result.

In stochastic programming the uncertain model parameters can be selected either randomly from their probability distribution or based on the knowledge of the analysts (called deterministic stochastic programming). The resulting uncertainty in decision variables is then solved using different methods (Sahinidis 2004):

- Recourse-based stochastic optimisation
- Probabilistic programming
- Fuzzy mathematical programming
- Stochastic dynamic programming

Algorithms and methods applying above mentioned and other methods have been developed in the Process Systems Engineering (PSE) community for chemical process design and synthesis purposes. These methods are applicable to early stage design aiming at screening based on techno-economic performance and uncertainty of the considered alternatives. The decisive factor in selecting the method is the goal of the design activity because of the different capabilities of the methods.

The most applied methods in design context are stochastic programming methods (see for example (Ierapetritou, Acevedo et al. 1996; Acevedo and Pistikopoulos 1998)). However, also other methods have been proposed. E.g. Svensson, Berntsson et al. (2009b; 2009c) describe a deterministic stochastic optimisation method for early stage retrofit design problems and demonstrate the method using a pulp mill retrofit investment project identification problem. Non-correlated uncertain model parameters are given a probability and a validity period, and are combined to sets to form future paths. The problem is solved using a multi-stage mixed-binary linear programming method. The combination of parameter uncertainty and time dependency of decision making leads in the case study analysis to a robust and surprising investment solution and proves the importance of uncertainty and time considerations in strategic investment decision making.

2.3.3 Critical aspect in uncertainty analysis

A challenge to all uncertainty analysis methods is the objective representation of the prevailing uncertainties in the second main step, quantification of the uncertainties. This is especially critical in the early phases of process design where in general less information is available and less accurate methods in design analysis are used.

Scoring methods often rely on ordinal verbal scales, and different perception and setting of the severity of each risk factor, and the perception of the scales in use can bring an additional uncertainty to the risk analysis results. In addition, invisible correlations between uncertain parameters can create false outcomes in scoring method analyses. (Hubbard 2009; Hubbard and Evans 2010)

Using stochastic methods can also be considered to be subjective and sometimes lack the decision makers' understanding of the underlying phenomena (origins of uncertainty) and therefore the probability distributions are only perceptions of the real distributions. (Bode, Schomäcker et al. 2007).

2.3.4 Risk analysis in biorefinery design

Cohen, Janssen et al. (2010) used a scoring method to establish technology maturity score for emerging biofuel production technologies in early stage design decision making for forest biorefinery. The technical maturity or level of development scale of different processing steps of ethanol production processes was assessed and given a subjective maturity score (value between 1 and 5). Thus, process related uncertainties were included in the analysis without quantification of the impacts of these uncertainties on the process performance using process simulation. The normalized sum of the technology specific scores was used as one decision making criterion among other criteria (including techno-economic, environmental impact, feedstock flexibility, product diversification and energy integration impact criteria). This technology uncertainty criterion was given a substantial importance in the MCDM.

Kazi, Fortman et al. (2010) studied several greenfield bioethanol production process design alternatives using corn stover as feedstock. Published process information was used as the basis for all cost analysis instead of future performance forecasts. The capital costs were *n*th plant estimates corrected with a factor based on regression modelling of 44 processing plants (pioneering plant analysis). The factor accounted for the uncertainty in capital cost estimate (level of design definition, e.g. process equipment not demonstrated commercially, or impurity build-up). Moreover, the production shortfalls during the start-up period were estimated using regression model, which accounts for the impacts of the development scale of the process and the complexity of the process on the revenue during the first years of production. In addition, investment cost contingency was increased to account for the uncertainty of estimating the *n*th plant capital costs. Scenario analysis was employed to evaluate the impacts of uncertain process parameters (specific to each studied process design) on product value. These uncertainties were based on literature and scenarios were constructed using minimum and maximum values found. Moreover, the generic economic assumptions and overall process parameters were assessed separately as sensitivity analysis.

In a recent concept demonstration level design analysis Laser et al. (2009a; 2009b; 2009) compared different biofuel and energy co-production process design scenarios. All design scenarios were assumed to be technologically mature, hence the used process parameters were assumed to represent processes with only incremental costs and benefit improvement potential. External uncertainties were considered using sensitivity analysis: feedstock cost, electricity and oil prices, and equity fraction were varied and IRR of the designs was evaluated.

These process creation and concept demonstration level design analyses utilized only the simplest methods (scoring, sensitivity and scenario analysis) for assessing the impacts of uncertainties in external factors and technological development level of the process. Similarly, Eggeman and Elander (2005) evaluated using scenario analysis the impacts of process parameters on minimum selling price of ethanol, Larson, Consonni et al. (2006) used scenario and sensitivity analysis for estimation of impacts of uncertainties in energy costs and monetized environmental benefits on black liquor gasification –based FBR project performance, and Papalexandrou, Pilavachi et al. (2008) evaluated the impacts of MCDM criteria weight uncertainty on the selection of transportation fuel substitution alternative for Europe.

Other more detailed design studies focusing on one process design only have also applied Monte Carlo analysis to estimate the impacts of external uncertainties on project performance (e.g. Aden, Ruth et al. (2002), Phillips, Aden et al. (2007), or Richardson, Herbst et al. (2006)).

In summary, only simple uncertainty analysis methods are applied in the early stage biorefinery and FBR design. Moreover, mainly external uncertainties are considered.

2.4 Decision making

2.4.1 Decision making in process design

At every stage of the process design process, screening or selection decisions are made. The decision making criteria can vary, e.g. economic, environmental, supply chain related or societal. Often these criteria are conflicting but should be considered simultaneously leading to a multi-criteria decision making (MCDM) problem. Sometimes, it is possible to reduce this problem to consider only one criterion by measuring all aspects of the decision making with the same units. Another alternative is to consider the different aspects one-by-one: using one criterion first for a decision can decrease the amount of design options and using another criterion on the pre-screened set of options, even more options can be screened out.

In the early process design stages the decision making goal is screening of design alternatives. Methodologies have been proposed for the early stage design screening using multiple criteria. For example, a pre-feasibility level method was developed by Hoffmann et al. (2001; 2004) to use multi-objective optimisation for screening of chemical process technologies including risk analysis. Cohen, Janssen et al. (Cohen, Janssen et al. 2010 utilized MCDM to rank emerging technologies for bioethanol production based on conceptual level design analysis (2010), and Hytönen and Stuart (2009) proposed an evaluation methodology (Large Block Analysis) at the conceptual process design level for retrofit biorefinery implementation into the forest industry considering project performance and project risk individually. In the latter case, no systematic decision making procedure was utilized, rather subjective screening was conducted based on the two criteria.

At pre-feasibility level with higher analysis accuracy, more sophisticated decision making methods considering multiple criteria can be used for ranking of design alternatives rather than only screening out less promising options.

2.4.2 Multi-Criteria Decision Making

If the decision alternatives are known, the MCDM problem can be solved using multi-attribute decision making (MADM) methods. This is often the case in process design when process configurations are set by available technologies and fixed in previous design stages. When the design alternatives are not known a priori, the alternatives can be generated and information for ranking these resulting alternatives can be obtained using multi-objective decision making (MODM) methods. This corresponds to a situation in which one or several decision variables are continuous (such as production rate, equipment capacities and amounts or unit parameters).

The overall MCDM procedure applicable to both these cases is illustrated in Figure 2.3 (adapted from Zhao (2002)).

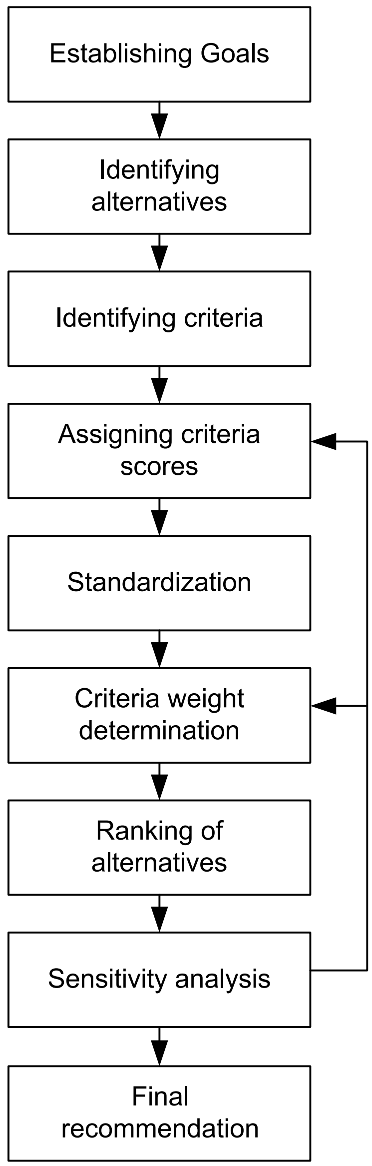


Figure 2.3 General steps of MCDM problem solving

Several methods applying the procedure exist, three often applied classes of methods are described in more detail:

- Analytical Hierarchy Process (AHP) is one of the most widely applied methods. This method is based on the work by Thomas L. Saaty (1980). It is a MADM method consisting of three main steps: 1) Hierarchical decomposition – the problem is decomposed into hierarchy levels (goal, decision making criteria, alternatives); 2) Evaluation – using paired comparisons of the decision making criteria against the goal and the alternatives against criteria the priorities are established. This can be done for example by a group of professionals; 3) Synthesizing results – the priorities are combined to overall priorities and after checking the consistency of priorities the solution is given. The reliability of AHP due to the ambiguity of the questions the decision maker must answer, has been considered to be one of the drawbacks of this method. (Dyer 1990; Harker and Vargas 1990; Saaty 1990)
- Multi-Attribute Utility Theory (MAUT) tries to quantify the decision maker's preferences through expected utility theory (Keeney 1982). It can be divided into four main steps: 1) problem structuring – goals and alternatives are defined; 2) alternative assessment – the alternatives are evaluated using defined criteria; 3) preference determination – utility functions (mathematical relation of human preference of an attribute over a range of attribute level) and weights (preferences between different criteria) are defined by decision makers; and 4) comparison of alternatives – alternatives are compared and sensitivity analysis is conducted. Alternative utility function shapes are linear, or exponential (convex and concave) functions, expressing risk-neutrality (linear), risk-proneness and risk-averseness of the decision maker respectively. Examples of MAUT -based methods are the Simple Multi Attribute Rating Technique (SMART) or generalized means method. Moreover, the weight values (second part of preference determination step) can be obtained using a trade-off method or a scoring method.
- Multi-Objective Optimisation (MOO) is one option to solve MODM problems. The solution of this approach is the optimum of considered alternatives, or in the case of multiple objectives, a set of Pareto optimal solutions. A decision maker weights the options inside the pareto optimal set of solutions. Four main types of MOO are: 1) No-preference method; 2) A posteriori method; 3) A priori method; 4) Interactive methods (described for example by Andersson (2000)). Generally only two objectives can be used because of visualization challenges, however, with interactive methods the decision maker can learn the behaviour of the problem at hand and can handle several objectives (Hakanen 2006).

All these approaches can be used with risk analysis. Alternative methods to incorporate risk are to 1) add supplementary criteria, e.g. minimum value to mark worst case scenario, and 2) use scoring methods to discount the criteria performances.

Different MCDM methods have been applied in process design in the forest industrial context. Janssen and Stuart (2007) used MAUT for determining the preferred retrofit design alternative based on economic and supply-chain level objectives utilising an expert panel. The study compared different thermo-mechanical pulp and de-inked pulp production scenarios combined with co-generation at an integrated newsprint mill. The main conclusion was that the panel decision making process managed to give a more balanced solution to the design problem and that this solution would not have been obtained using a traditional economics-based decision making process.

Andersson (2000) surveyed the use and applicability of various optimisation based methods in engineering design context, focusing on MOO. Furthermore, Hakanen, Hakala et al. (2005) used an interactive MOO method (developed by Miettinen and Mäkelä (1995)) linked to a process simulator in designing the heat management of a paper machine. The objectives were to minimize heat demand, the heat exchanger surface area and cooling and heating demands of effluent in winter and summer conditions. Normally this type of problem would be simplified to a single-objective optimisation by annualising the different costs. However, in that case the interconnection of the objectives is not transparent anymore. The main conclusion of the case study was that the interactive method can significantly help chemical process design decision making by increasing the understanding of the implications of different decisions.

In the biorefinery process design context, MCDM methods have not been widely utilised. Papalexandrou, Pilavachi et al. (2008) used the AHP method to evaluate different biofuel production options. They used the biofuel production cost (economic), bio-fuel yield (potential of the process to replace fossil based fuel production), total cycle green-house gas emissions (environmental impact) and total cycle energy consumption (resource demand for vehicle motion) as criteria for selecting suitable biofuel production scenarios in an European context. 22 different scenarios were considered including both first and second generation bioethanol and bio-diesel and syn-diesel options. The three most promising options were selected. Interestingly, the set remained the same even if the priority of the criteria was changed. Hence, a robust screening was obtained.

Cohen, Janssen et al. (2010) analysed emerging technologies for ethanol production in an integrated forest biorefinery using a trade-off MCDM method. A scoring method was utilized to measure process inherent uncertainty. Uncertain technical maturity or the level of development scale of the different processing steps of ethanol production processes was considered by assessing each processing step and giving it a subjective maturity score. The normalized sum of the technology specific scores was used as one decision making criterion among other criteria (including techno-economic, environmental impact, feedstock flexibility, product diversification and energy integration impact criteria). An expert panel gave a substantial importance to the risk criterion.

The wide application of many different MCDM methods shows on one hand that these methods have developed to sufficient level, and on the other hand that often the design decision making requires the consideration of multiple dimensions and traditional decision making using a single criterion is not sufficient for the decision making. However, choosing the most suitable method for the specific decision making context is not necessarily always done as is commented by Dyer (2005) in the case of selecting an MAUT method.

Moreover, the design decision making related MCDM literature has been focusing on the economic and environmental aspects that are often conflicting. However, in strategic investment decision making the financial criteria alone can already be conflicting. Good strategic fit (in financial terms) and project performance are not necessarily linked to each other.

2.5 Strategic capital spending planning

In a modern strategic planning process, the mission and drivers such as the global economy, environmental regulations or resource productivity influence the company strategy. This strategy is reflected in plans and further realized through various programs (Goldman 2000). For example, strategic investment projects belong to investment programs including all asset management actions (investments into new products, into platforms such as change in competition basis, and investment into existing production system) (Cooper, Edgett et al. 2002). Thus, the connection between a single capital investment project and the company strategy is often considered to be one-directional (Northcott 1995; Komonen, Kortelainen et al. 2006; Åberg 2006), even though an information link between asset strategy and individual project exists (see Figure 2.4) (adapted from Komonen, Kortelainen et al. (2006)).

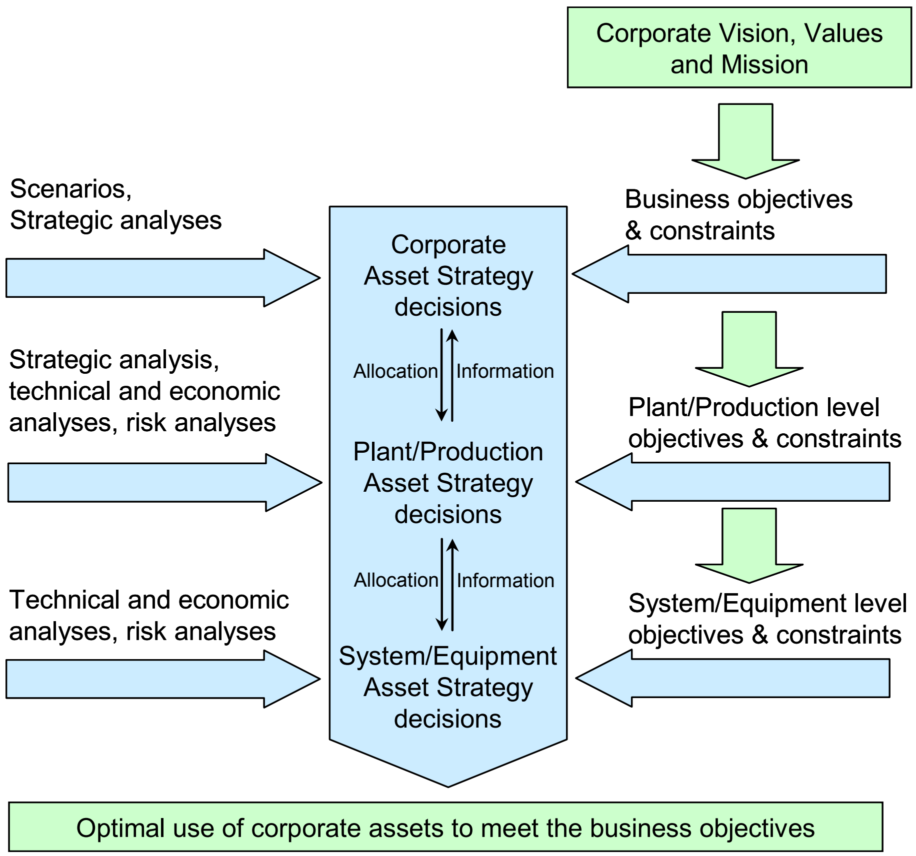


Figure 2.4 Strategic asset management levels and inputs to decision making

Carr, Kolehmainen et al. (2010) investigated the trends how strategy actually impinges on management accounting practices in both stable and dynamic market settings. For example, the geographic region implies some preferences and use of criteria (e.g. age, financial structure), or, a different business orientation (e.g. market creator vs. refocuser) allows different hurdle rates and payback period expectations in capital appropriation.

This originates from several aspects, including a company's internal rewarding systems, performance measures, management accounting, capital budgeting and project appraisal, and can result also in short-termism in decision making and against investment in new technologies. Especially traditional management accounting systems are not capable to reflect all information gathered in capital investment decision making process. (Nixon 1995)

2.5.1 Capital investment project feasibility evaluation

Capital investment project appraisal after investment strategy development in manufacturing industries generally follows a five step process: 1) Identification of potential investments; 2) Project definition and screening; 3) Analysis and acceptance; 4) Implementation; 5) Monitoring and post-audit (Northcott 1995; Åberg 2006; Götze, Northcott et al. 2008; Kivijärvi and Tuominen 2008).

The same appraisal process is often applied to the main types of capital investment projects, infrastructure, strategic and operational (or foundational, supplementary and current (Götze, Northcott et al. 2008)). However, the decisions are normally made at a different level in the organisation leading possibly to a slightly different need for decision making criteria (three decision making levels, Figure 2.4). This conventional 5-step approach is especially useful in operational investment projects that consider normally only the tangible fixed assets but is not sufficient for infrastructure and strategic investments. In the retrofit investment opportunity analysis case, the two relevant types of capital investments are operational and strategic projects:

- Operational projects, where the objective is to preserve existing assets' productivity or make non-production related plant enhancements (e.g. environmental or safety projects). Usually, operational projects are smaller cost investment projects that can be made with internal financing (annually allocated funds from cash flow)
- Strategic projects are intended to significantly enhance the existing production capacity or change the business strategy, for example adding a new product to the product portfolio. For these projects additional external financing might be needed (debt and/or equity)

A UK survey by Alkaraan and Northcott (2006) suggests that, contrary to the textbook literature and academic research, in practice there is no significant difference between the operational and strategic investment decision making process. However, the importance of the above described conventional financial investment appraisal process results and the non-financial criteria, e.g. intangible project attributes like future flexibility provided by the investment, differs: financial analysis is more used and better applicable to short-term projects, whereas non-financial criteria are more important in strategic decision making.

The same study also surveyed the use of different strategic investment evaluation methods proposed in the literature. It included the balanced scorecard, real options analysis, value chain analysis, benchmarking and technology roadmapping methods. The main conclusion is that only benchmarking is relatively widely used and the others are not well applied, partly due to their complexity. Another reason could be that the methods are not capable of providing useful information of investment projects, hence more easy-to-use methods providing useful, non-financial information would be needed to be able to better connect financial and strategic planning in the company.

US based surveys by Farragher et al. (1999) looking at capital investment practices and Hogaboam and Shook (2004) investigating performance measures use in the US forest industry capital budgeting and rationing show similar results:

- Corporate strategic factors, such as potential competitive advantage, or markets, are a key component in investment decision making.
- Decisions are mainly made based on developed investment goals (strategic and financial).
- IRR and NPV are the main techniques used.

Hogaboam and Shook (2004) also confirm the known practices in risk analysis: sensitivity analysis and subjective adjustment of cash flows are the most commonly used. Major uncertainties considered are the risk of not obtaining the target return, uncertainty about the market potential and uncertainty about entering an inexperienced area. Thus, proper criteria for these would be preferred in decision making.

Important to a company in addition to a successful individual investment project implementation is a good project track record. Jortama (2006) studied the self-assessment methods for developing the capital appropriation process in a paper mill context. Three perspectives with multiple criteria measuring them (risk, targets and strategy) were proposed to evaluate the quality of the investment project. The methodology was applied in a large paper mill investment project post-completion audit based on all available documentation and involved peoples' knowledge.

2.5.2 Application of product costing methods in capital appropriation

Utilisation of advanced costing methods in strategic investment decision making have been proposed:

- Angelis and Lee (1996) proposed a methodology for utilising ABC already adopted for accounting in a company as a costing method for evaluating cost-impacts of investment strategy on individual activities. These impacts, or changes in resource costs due to investment, are aggregated into an overall impact using ABC and then used in parallel with another criterion that measures the impact on the company performance. The performance measure is a result of a two-step analytical hierarchy process (AHP) in order to establish a strategic fit score for the investment. The investment selection is then made based on a visual method (plot of cost impact vs. performance impact), thus combining performance of the investment with regards to cost savings and fit to strategic goals such as quality, capacity and productivity is considered.
- Sawhney (1991) used activity-based modelling to evaluate the investments' performance related to manufacturing strategy components (e.g. capacity, productivity, lead time, quality). Measures of performance are often based on costs at the activity level (a productivity measure such as price of output per overhead costs, or a flexibility measure such as price of output per setup time), and therefore a form of ABC was utilized. The methodology presented in this research linked the activity-based modelling to investment selection and evaluation at different phases of the investment process using multi-criteria decision making methods.

Another use of ABC extending from an investment project alone to costs of the entire life of the invested asset is in life-cycle costing (LCC). For instance, Emblemsvåg (2003) and Rivero and Emblemsvåg (2007) have used ABC to evaluate life-cycle costs of different long-range scenarios (budgeting scenarios) of a facility or a company. ABC enables the identification of key success factors of a scenario and a better-informed comparison of scenarios through its higher transparency.

2.5.3 Business performance and company valuation

The two main business valuation methods are based on 1) the value of the asset, and 2) the actual or perceived earning power of the company (Doyle, Jr. et al. 2004). The first method uses different discounted cash flow procedures, and often used measures are net present value (NPV) or internal rate of return (IRR). The second method is connected both to the company and to the stock market: the valuation is based on multiples derived from market values of similar companies and some company specific performance metrics such as cash flow or net earnings. For instance, average price per share to earnings per share (P/E) ratio based on similar publicly traded companies can be used to estimate the stock price per share of a company. The main difference between these methods is that the first method is heavily impacted by the capability to forecast the future cash flows needed in the NPV estimation, whereas the latter method relies only on cash flow of one year, e.g. cash flow of the previous calendar year. On the other hand, the challenge of the multiple –based valuation is in defining a representative multiple and evaluating it. This results from the difficulty to unambiguously value a company above, below or at the industry average (Doyle, Jr. et al. 2004). In addition, it is difficult to establish these multiples for emerging industries such as for biorefinery industry.

Commonly used valuation metrics utilize cash flow statement from previous accounting periods as the basis of investment evaluation. Different techniques are able to capture the viewpoint of different stakeholders at different times. For example, after a major part of the asset is depreciated, a valuation based on only operating profits is representative, whereas after a significant capital investment the capital charges should be included in the analysis. On the other hand, multiple-based valuation methods are not best suited for internal capital investment project comparison in a company due to the large ambiguity in estimating potential impacts of an investment on the business environment defining the value of the company. (Harper 2005)

The main economic drivers in strategic planning are the stock holders' and debt holders' needs (Goldman 2000). This translates into the need to use suitable metrics for justifying a strategic investment. Even though attempting for a process engineer to use the traditional investment project appraisal because it resembles the process design process from a company point-of-view, the valuation of the entire company can be very important for the stakeholders. Some frameworks have been proposed and used for evaluation of the business performance based on process knowledge and design:

- Howell, Hanson et al. (2002) presented the management of process-asset lifecycle through virtual-asset models. This approach integrates the physical asset through engineering (process design activities) with the business lifecycle. The interactive formulation of the models enables two-way communication between the business lifecycle and the physical asset. Experience of implementing this model centric approach shows potential to lower the overall production costs up-to 15% and to reduce the capital investment costs of revamp projects with about 4% in some cases.

- In the forest industrial context, Kivijärvi, Tuominen et al. (2001) have developed a system dynamics -based Decision Support System for strategic planning in Finnish forest industrial corporations. They defined a modelling system with sections dedicated to process operations (pulp and paper production, saw mill, etc.), marketing activities and management in forest industries. This corporate-wide simulation system is the core of the framework. Around the core, AHP-based decision making is used with Group Support System thinking. As an example, UPM-Kymmene Corporation was used. They describe the step-wise implementation of the system into the corporate strategic planning, the different modules of the system, eight hypothetical strategies, the criteria to evaluate them and the evaluation process. The example was only educational and no real case study results were presented.

The strategic investment decision making is often linked to business performance analysis through the use of project performance metrics. However, the business performance is also analysed using other sources of data than the investment project analysis to account for the overall asset. Moreover, the investment project analysis is not necessarily systematically linked process design analysis and thus the link between process impacts and investment decisions is not evident.

2.6 Gaps in the body of knowledge

Based on the literature review the following holes in the body of knowledge were identified:

Design methodology

There is no retrofit design methodology available that, by systematically linking process simulation and advanced multi-product costing, is able to derive 1) retrofit cost-impact data, 2) retrofit project economic performance metrics, and 3) company level performance metrics for capital investment decision making considering relevant uncertainties. Thus, no retrofit design methodologies exists that are able to well link process design with strategic investment decision making.

Risk analysis

To our knowledge, process design risk analysis showing simultaneously the impacts of different types of uncertainties including feedstock cost uncertainty, uncertainty in technologies and product markets on worst case scenario project performance have not been carried out for retrofit design decision making.

Retrofit project costing

There is no activity-based costing –like retrofit design methodology that systematically assesses the changes in manufacturing costs of current products due to retrofit implementation of new product production lines for capital investment project evaluation.

Evaluation of capital spending strategies

There are no design methodologies proposed in the literature, that expand the pro-forma cash flows of investment project analysis to the needs of strategic investment decision making by measuring the financial performance and risk of the capital spending strategies at project and facility levels, and utilizes panel-based trade-off capital investment decision making.

CHAPTER 3 OVERALL METHODOLOGICAL APPROACH

3.1 Overall methodology

Retrofit implementation of the biorefinery into a kraft pulp and paper mill has integration impacts at several levels. Resulting changes in production costs of existing products and overall performance of the facility because of these changes can be estimated using a new retrofit design decision making methodology developed in this work (Figure 3.1). This methodology is best suited for the capital appropriation phase in an overall decision making process of a company (e.g. concept demonstration and pre-feasibility design stages).

The methodology consists of four main steps:

1. Large-block analysis followed by screening out non-potential retrofit designs
2. Operations-driven cost analysis of capital investment candidates
3. Mill-level performance analysis of the candidates, and
4. Multi-criteria decision making to obtain preferred capital appropriation scenarios

Biorefinery retrofit implementation project analysis requires several different types of data with increasing level of detail through the design process. The data can be divided into four classes: 1) new process/technology technical data, 2) raw materials, 3) products, and 4) existing facility related data. In Figure 3.2 details of each category are shown. This scheme is applied in main steps 1 and 2 (advanced mill-level costing requires a higher level of detail in all classes compared to the traditional techno-economic analysis).

For the pro-forma cash flow analysis used in project and business-level evaluation, estimates of future trends of product prices and raw material supply-curves were also assessed. Moreover, in risk analysis, possible trend scenarios or probability distributions, of the uncertain trends are needed. Publicly available information and the expectation of market developments were used to obtain these data and to evaluate correlations between the different uncertain trends.

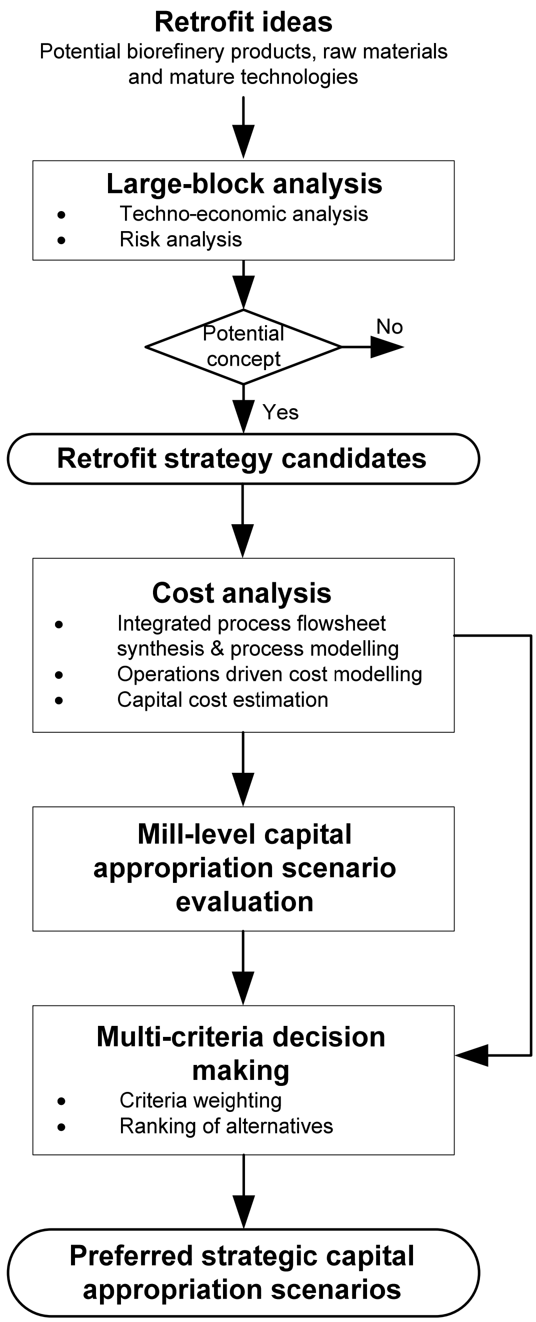


Figure 3.1 Overall methodological approach

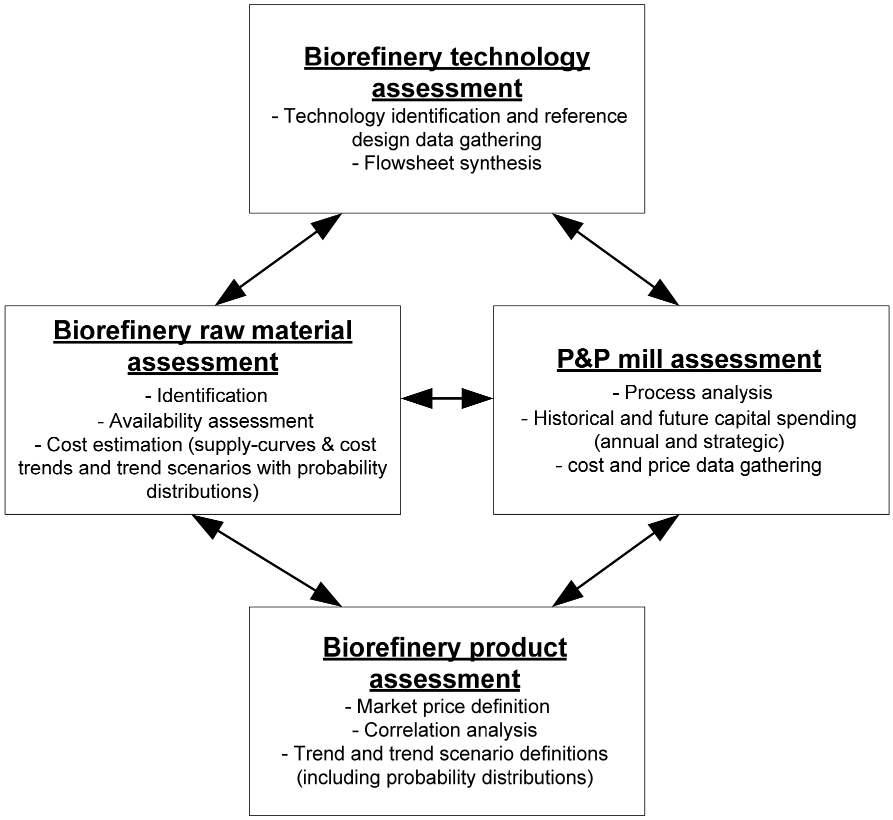


Figure 3.2 Overall scheme for data gathering for retrofit design analysis

The following sub-sections further describe each step of the overall methodology.

3.1.1 Large-block analysis

A traditional techno-economic analysis was used for technology pre-screening and for providing benchmark data of the method used in a traditional capital appropriation. Large-block analysis (see Figure 3.3, Hytönen and Stuart (2010)) was used, in which processes that are implemented in retrofit are considered using input–output-models in order to calculate their mass and energy balances. Conventional techno-economic analysis and risk analysis are utilized to analyse the new process designs considering existing processes.

Feedstock supply-curves (cost of feedstock as a function of feedstock capacity) are first estimated based on biomass databases and cost models accounting for the variable and fixed costs of the crop, harvesting and transportation (model described e.g. in report Arthur D. Little Inc. (2001), or by Lynd, Wyman et al. (2005)).

Then, the capital investment costs are estimated using department-level dimensioning (factorial scaling using ”standardized” factors for all retrofit designs to have commensurate estimates) based on published cost estimates. The mass and energy balances are used for O&M cost analysis. Costs are estimated as a function of production capacity to be able to identify low cost production capacity for each alternative. At a low cost design capacity, sensitivity analysis is conducted in order to identify variables that have significant impact on the performance and that can vary substantially. These variables are then used in multivariate stochastic analysis (Monte-Carlo analysis) to obtain probability distributions of the performance of all design alternatives, and to screen out clearly less promising retrofit design alternatives.

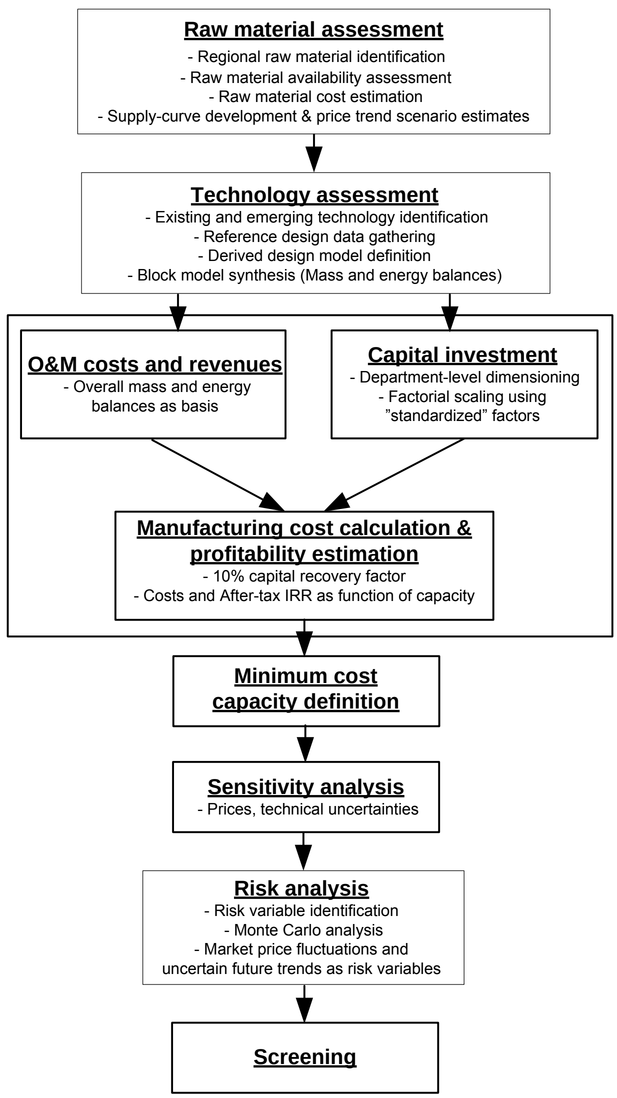


Figure 3.3 Large-block analysis method

3.1.2 Cost analysis

The core of the overall methodology for aiding the capital appropriation is the operations-driven cost modelling framework for product costing. A three-step retrofit process design analysis sequence is applied in the development of the cost models of the retained design alternatives:

1. Development of the base case model,
2. Validation of the base case model using process data and financial statements and reports, and
3. Development of the cost models of the retained retrofit cases.

The flowsheet synthesis and process design following traditional design principles serve as the basis for the steady-state process simulation, and consecutively for the O&M cost and capital investment cost analyses. Steady-state process simulation models – either existing process simulation models of the current facility, or new/modified models based on the flowsheet synthesis – provide the cost models with resource and activity drivers that are based on the mass and energy balances. Moreover, the integrated designs' mass and energy balances and flowsheets provide utility demands and constraint information of the current systems needed in equipment dimensioning.

In the development of this framework, first the base case mill simulation model is developed and validated based on available mill data. Flowsheet synthesis of the retrofitted mill configurations is done simultaneously with the process simulation model development. This guarantees that existing system constraints are not exceeded, and new equipment is included in the designs when existing equipment's capacities are fully utilized. In this work, the simulation models were constructed using the commercial process simulation software Balas®[1]. The mass and energy flows between defined cost model activities represented by the steady-state simulation model are then transferred to the cost models using driver and production rate tables. These cost models were developed in this work using Impact: EDC™ from 3C Software Inc[2]. A similar procedure in the model development as with process simulation models is used: the base case cost model is

[1] http://balas.vtt.fi/

[2] http://www.3csoftware.com

first validated using financial data from the mill, followed by development of the retrofit scenario cost models. In the case when base case cost models (process and ABC models of the mill) would exist, the first two steps can be omitted.

A retrofit scenario is represented in the cost model as a cost object. This cost object consists of all the products of that scenario. Different driver types are utilized in ABC to describe the consumption of resources and activities (by other activities or cost objects), see Figure 3.4. Because many of the inter-activity activity-drivers and cost object activity-drivers (activity consumption by cost objects) in chemical processes are based on continuous material flows, the ABC-type definition of them can be re-defined (see Figure 3.5) to better utilise the basis of these drivers. These activity-drivers can be converted to pairs of intermediate resource driver - intermediate resource, where the intermediate resources are products of activities. Examples of these are different by-product streams or very high pressure steam (VHP) and process steam or bleached pulp. Thus, some of these intermediate resources are consumed by the activities and others by cost objects. Converting the complex inter-activity activity-driver and cost object activity-driver matrices to a resource driver–like syntax enables easier tracking of changes in the costs. Because the intermediate “resources” are products produced by activities, their costs (cost flows carried by these intermediate resources) are defined based on the corresponding rule of allocation in the producing department.

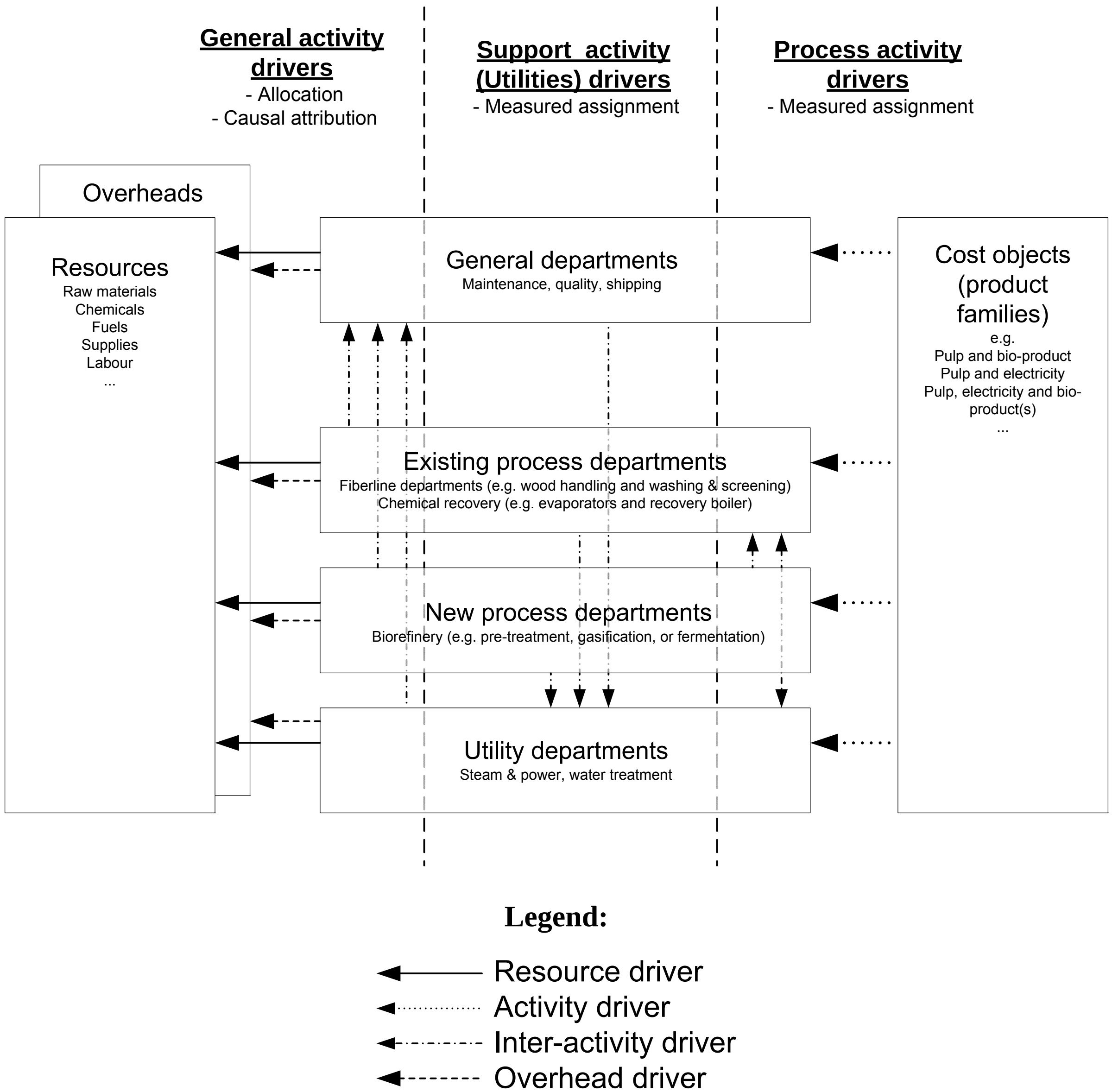


Figure 3.4 Definition of drivers in conventional ABC costing

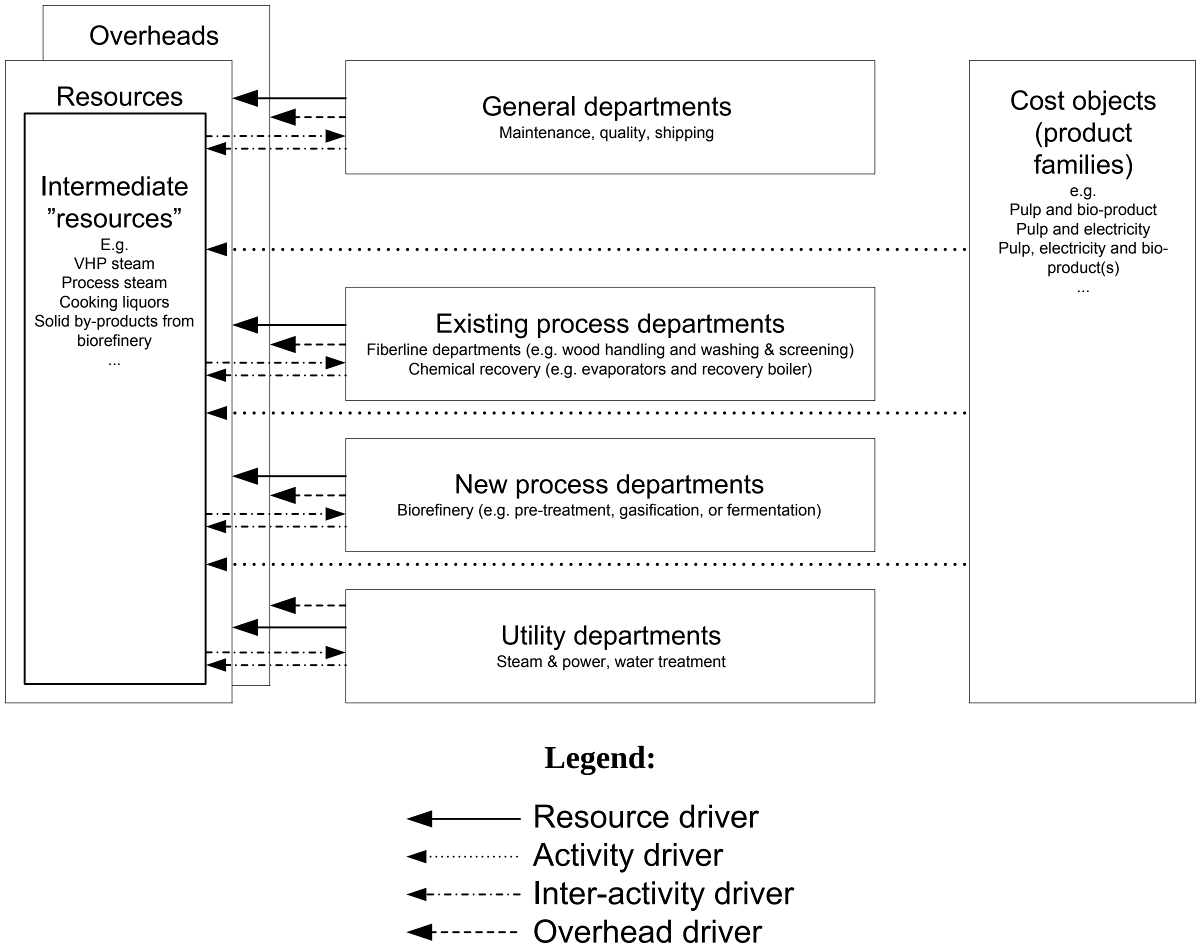


Figure 3.5 Re-formulation of cost object and inter-activity activity-drivers for operations-driven costing for continuous multi-product facility

All drivers and allocation table are formulated as sparse matrices (each department or unit operation represents a vector in this matrix, consumed resources and intermediate resources, and the streams carrying costs have non-zero value). Cost flows with fixed unit cost (e.g. process water and wastewaters that are passed between departments before sending them out from the facility) carry part of the costs and are considered as an inward cost flow, or a cost to an activity.

The sparse matrix formulation increases the computational requirement of the cost modelling but it is important to be able to quickly analyse significantly different process configurations in the early stage of process design. Moreover, the time saved in not developing cost models that are optimal from a computational standpoint for all designs can be significantly higher than the computation time. In addition, this cost model structure can be used in normal cost accounting.

Analysis of many retrofit alternatives at the early design stage benefits especially from this approach because of two reasons: 1) utilization of intermediate resources makes it easy to add new designs, 2) the sparse-matrix formulation of drivers and allocation rules connected to process simulation models enables easy translation of mass and energy balances into cost information.

For example in the case of adding power production capacity by investing in a steam turbine, adding a new steam turbine using the traditional ABC definition would require re-routing the VHP and process steam drivers between all old and new departments producing and consuming VHP and process steams. Using the developed intermediate resource -structure, the new steam turbine activity added to the cost model consumes a pre-defined intermediate resource, and produces other pre-defined intermediate resources and updates their cost flows accordingly. Moreover, the added activity adds only one column to the sparse matrices, and the cost calculation follows directly the balances and adjusted other driver definitions.

The overall method for constructing an ABC model for cost accounting purposes is therefore modified to be used in the development of the ABC-like operations-driven cost models of the design alternatives (Figure 3.6).

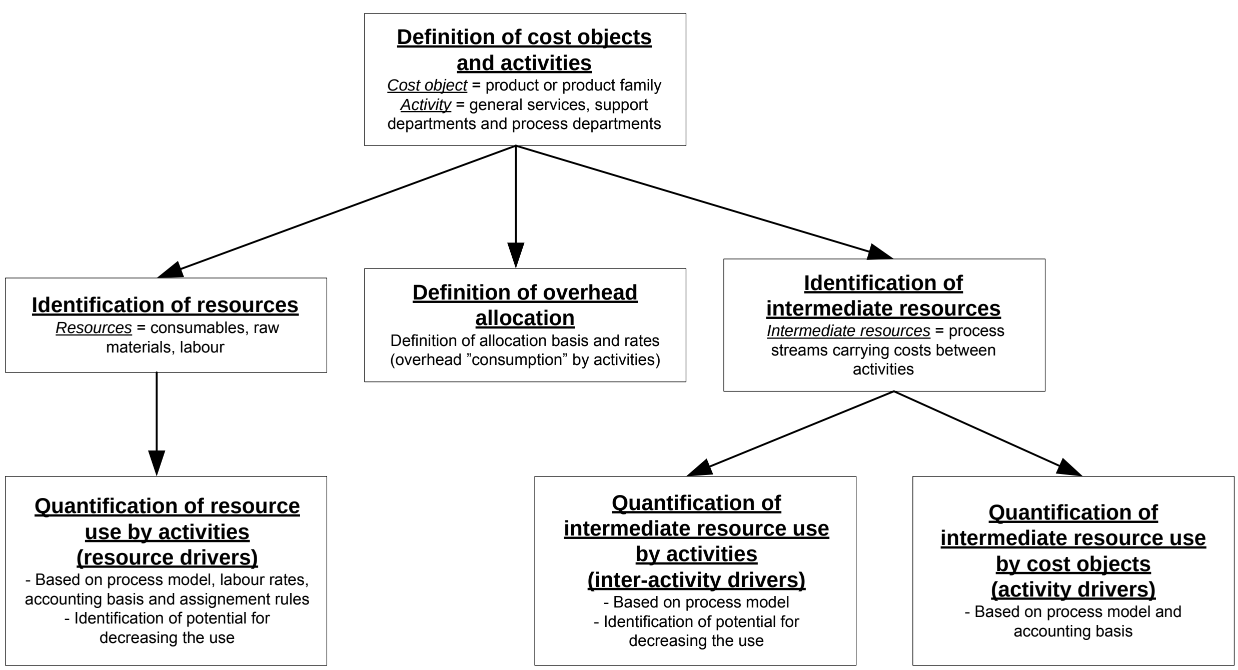


Figure 3.6 Method for developing an activity-based cost model

In the cost model development, the information gathering scheme (Figure 3.2) is used. For a good fit of the cost modelling to strategic capital investment project analysis based on operations, a strong link between simulation models and cost models is required. This is obtained by:

- The same resources and activities (process departments) are used in the simulation and cost models to obtain the driver information from the simulation models (drivers that are material and energy flow-based). In the ABC cost models used in accounting, this data link would exist between the cost model and information management system.

- Estimates of potential for enhancements in the existing system (minimum level of labour required for an activity, targets for energy efficiency, reliability, productivity) and the annual costs for achieving these targets are used to define the trends of drivers, cost assignment bases (cost assignment between several products of an activity) and allocation of overheads in the company. These are defined at the cost model-level, considering the mill’s accounting principles.

Capital related costs (annual depreciation, amortization, impacts on maintenance costs) are calculated based on gathered data. Retrofit project capital investment costs can be estimated using standard methods described in 2.1.4.2 using the synthesized flowsheets. Capital spending history defines the depreciation, and historical performance in annual capital project execution can enhance the estimates of capital costs of performance enhancement projects.

The results of an operations-driven cost model are product costs, activity costs and uncertainty in these costs in all design scenarios. These were further used in financial performance analysis.

3.1.3 Retrofit project evaluation at the mill-level

Evaluation of capital spending scenarios follows three main steps:

1. Definition of performance criteria

2. Definition of measures for the performance criteria

3. Quantification of the measures

In the first step, contextually relevant economic performance criteria are selected. This is achieved through understanding of the key performance factors in the business environment. Examples of the factors are the cost structure of produced products, cost competitiveness of the products, location specific uncertainties in the business environment such as feedstock and product markets, and criteria for capital performance that stakeholders, investors and banks use in investment decision making.

The second step is needed to identify a suitable measure to quantify the criterion. Different financial metrics used currently are not necessarily sufficient measures for the identified critical performance factors and are therefore modified to better reflect the criterion.

The third step evaluates the investment strategies using the identified measures. Further, ranking of the design alternatives can be obtained using a systematic decision making method. In the next section, the decision making method used in this work is elaborated.

3.1.4 Multi-criteria decision making

The multi-criteria decision making process follows the procedure shown in Figure 2.3. In this work the goals are identified by the design process and alternatives are defined through pre-screening of design alternatives, thus the design process identifies the alternatives considered in the MCDM. Furthermore, the criteria identification and criteria intensity evaluation are achieved through the cost analysis and investment strategy evaluation steps of the methodology.

In this work, MAUT was used for decision making and the criteria weighting step utilized a panel-based trade-off technique (suitable for MAUT methods) to assess the importance of a decision making attribute (Beinat 1997). MAUT methods were originally developed for analysis where cardinal information about the attributes exists. A comprehensive classification of different MADM methods supporting this selection is presented for example in the book by Gotze, Northcott et al. (2008) for the case of capital investment project multi-criteria decision making analysis. Moreover, these methods are designed for decision making under uncertain conditions but also suit well for decision making under more predictable conditions. In this work uncertainties in the system are assessed through separate decision making criteria and all criteria are therefore certain.

The decision making panel judges indifferences among multi-attribute profiles by estimating an attribute score of the most important criterion which makes the assessor feel it indifferent to another criterion at its maximum score. This means, that for each criterion the value of the most important criterion which makes the other criterion at its maximum value as important to the panellist is assessed. The most important criterion is selected by the panel in unison, however the indifference judgements are individual estimations of each panel member to account for all stakeholder opinions.

An important characteristic of the MAUT-methods is the utility functions that describe the preferences of the decision maker over a range of attribute levels. These functions were assumed to be linear between the attribute boundaries. Boundaries for each attribute were the minimum and maximum values among the alternatives, except for criteria that are contextually bounded (project performance and project risk that are bounded to always be positive). Moreover, the total utility function is assumed to be additive following the equation 4:

$$U(x) = \sum_{i=1}^{M} w_i u_i(x_i) \qquad [4]$$

where $U(x)$ is the total utility, w_i is a weight of the attribute i, and $u_i(x_i)$ is the utility of the attribute i. The summation goes through all M attributes.

Finally the ranking of alternatives can be obtained using the averaged weights of the panel and the utility functions, and sensitivity analysis can be conducted using the dispersion in the panel member trade-off values.

3.2 Case study introduction – retrofit forest biorefinery implementation

3.2.1 Background

Integration of biofuels production into a North-American hardwood kraft pulp and paper mill was considered as a case study in this work. The case mill is surrounded by different types of raw materials suitable for a biorefinery, and potential end users for the produced biofuels and bio-products are in the vicinity of the mill. Moreover, the raw material pool in the mill region is used by many users and this indicates that lower biofuels production volumes could potentially be more economical than large volumes due to the cost of feedstock. This is somewhat in contradiction to many analyses done purely based on transportation costs (e.g. literature reviewed by Galbe, Sassner et al. (2007), and the analyses of Wright Brown et al. (2007) and Stephen, Mabee et al. (2010)).

Also other bio-products are of interest, and a traditional mill modernization project is competing with the possible biorefinery implementation projects for the same capital.

3.2.2 Base case

The base case kraft pulp mill is producing pulp (wet and in ~50% dryness) at a production rate of 1200 ADMT/day. The integrated paper mill producing fine paper is not considered in the case study in detail since the biorefinery process would be integrated into the pulp mill only. Nevertheless, the cost impacts of the integration at the paper mill are also included in the analysis. Moreover, the current intermediate product pulp is assumed to be an end product and saleable at an adjusted market pulp price for economic analysis purposes. A simplified block diagram of the case mill is shown in Figure 3.7.

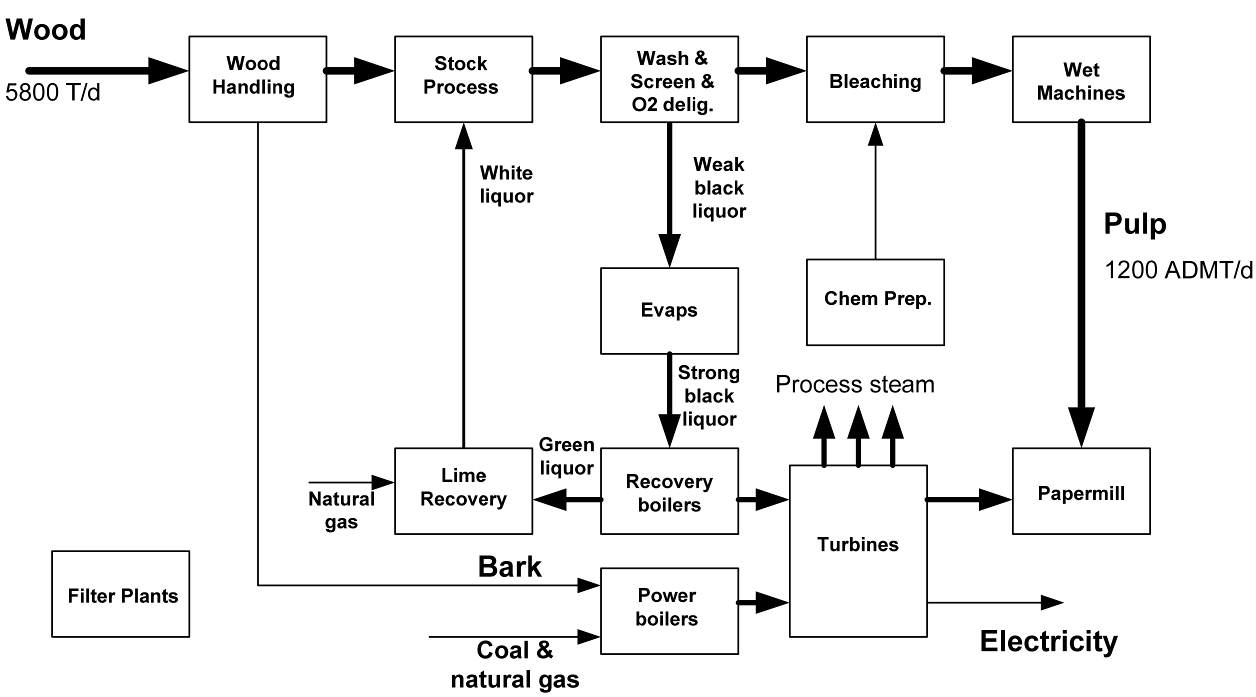


Figure 3.7 Base case mill block diagram

The mill has two separate fibre lines, three recovery boilers, three power boilers and two steam turbines. From the boilers, one is natural gas fired and used only when required (for example during winter months). The turbines and filter plants have some excess capacity to meet potential biorefinery process demand.

The mill is increasingly investing in replacement equipment and maintenance to keep the mill operational. Moreover, annual investments are used to further enhance the mill's performance to lower production costs and to comply with regulations. These are required because the last significant investments into the production system and utilities were done in the 1990s and all major production related unit operations are already operating over their design capacity.

3.2.3 Strategic retrofit capital spending strategies

A total of 42 feedstock-process-product combinations for production of bioethanol, mixed alcohols and Fischer-Tropsch liquids for fuels or waxes were initially identified as potential retrofit alternatives for pre-screening. These alternatives used woody biomass, pulpwood, hemicelluloses, lignin, corn, corn stover or food-processing wastes as feedstock, and the production rate was not fixed. A more detailed description of the alternatives can be found in (Hytönen and Stuart 2009; Hytönen and Stuart 2010).

From these alternatives, the retained biorefinery designs after pre-screening and the traditional mill modernization project are described in Table 3.1.

Table 3.1 Retained retrofit capital investment alternatives

Feedstock	Process description	Products	Design capacity	Feedstock capacity
Pulpwood	Modern Kraft pulping process and chemical recovery cycle utilizing maximum amount of existing pulping process equipment	***Kraft pulp***	1650 BDT pulp/day (35% increase from base case capacity)	1.5 million bdt/year
Hemicellulose extract	Value-prior to pulping (VPP): Near-neutral green-liquor extraction Acid hydrolysis Liquid-liquid separation Fermentation & distillation	***Ethanol*** Acetic acid Furfural	base case – 23 ML/year (6.1 MMGPY)	10% of pulp wood
			modernized – 30 ML/year (8.0 MMGPY)	10% of pulp wood
Corn stover Co-processed with kraft pulp, using mill infrastructure to maximum extent	Biochemical lignocellulosic ethanol: Dilute acid pre-treatment Enzymatic hydrolysis Fermentation & distillation	***Ethanol*** Organic solid residue	95 ML/year (25 MMGPY)	0.25 million bdt/year
			379 ML/year (100 MMGPY)	1 million bdt/year
Forest residues Bark co-processed with kraft pulp, using mill infrastructure to maximum extent	Thermochemical Fischer-Tropsch: Drying & grinding Steam reforming Syngas cleaning and compression FT-synthesis	***FT-liquids*** Energy	37 500 bdt/year	0.25 million bdt/year
			150 000 bdt/year	1 million bdt/year

Due to the different production scales, complexity and utility demand of the projects, significantly differing capital investment costs and therefore different construction periods would be needed. The mill modernization project is assumed to take 3 years whereas all biorefinery projects would be completed in 2 years. Independent of the total project costs, the capital structure for the financing is assumed to be the same (100% equity) for all alternatives.

The defined strategies imply also different annual capital spending after the project completion: mill modernization significantly lowers the need to replace older equipment, whereas biorefinery implementation into the base case mill will not impact the pulp mill's maintenance need. Similarly, improvements in performance (reliability, energy efficiency, productivity) are increased through mill modernization and therefore annual performance improvement investments are expected to be significantly lower.

CHAPTER 4 PUBLICATION EXECUTIVE SUMMARY

4.1 Presentation of publications

The following articles that are published in, or submitted to peer-reviewed scientific journals can be found in Appendices A to D of this thesis.

- E. Hytönen and P. R. Stuart, "Integrating Bioethanol Production into an integrated Kraft Pulp and Paper Mill – Techno-Economic Assessment", Pulp & Paper Canada, vol. 110, pp. 58-65, 2009. Republished in TAPPSA Journal, November, pp. 17-24, 2009

- E. Hytönen and P. R. Stuart, "Biofuel Production in an Integrated Forest Biorefinery—Technology Identification under Uncertainty", Journal of Biobased Materials and Bioenergy, vol. 4, pp. 58-67, 2010.

- E. Hytönen and P. Stuart, " Operations-driven cost-impact evaluation of kraft process retrofit projects for capital appropriation: case of forest biorefinery", Submitted to International Journal of Production Economics

- E. Hytönen and P. Stuart, "Design methodology for strategic retrofit biorefinery capital appropriation", Submitted to TAPPI Journal

Other complementary publications listed below are included in Appendices E to H.

- E. Hytönen and P. R. Stuart, "Capital appropriation for the forest biorefinery", Submitted to Pulp and Paper International

- E. Hytönen and P. Stuart, "Techno-Economic Assessment and Risk Analysis of Biorefinery Processes" in Integrated Biorefineries: Design, Analysis, and Optimization. In Review, M. M. El-Halwagi and P. R. Stuart, Eds.: CRC Press/Taylor & Francis, 2012

- E. Hytönen, R. B. Phillips, and P. R. Stuart, "Estimation of the cost impacts of retrofit biorefinery implementation using operations-driven costing" in Proceedings of the 2010 AIChE Annual Meeting, Salt Lake City, UT, USA, 2010

- Hytönen, E. and P. Stuart, "Techno-Economic Assessment and Risk Analysis of Biorefinery Processes" in Proceedings of the 21st European Symposium on Computer Aided Process Engineering, Chalkidiki, Greece, Elsevier, pp. 1376-1380, 2011

4.2 Links between publications

The theoretical background of process design under uncertainty was reviewed in order to be able to link the important uncertainties in the industrial context of this Ph.D. work with the suitable risk analysis methods and the process design stage in the research focus. This review was presented in the 21st European Symposium on Computer-Aided Process Engineering in Greece (2011) (Appendix H) and is reported in more detail in a biorefinery design book chapter (Appendix F, book to be published in 2012). In addition to the review of theoretical approaches for design under uncertainty, biorefinery case examples from literature and a concretizing case study were presented in these publications.

The case study work is described in detail in the Appendices A and B. This case study was further elaborated for risk analysis in the review of process design under uncertainty. These early design stage case study papers present the analysis of retrofit biorefinery implementation into a kraft pulp mill using traditional techno-economic analysis and stochastic project risk analysis, and the screening of alternatives based on this analysis. This case study work was done in order to 1) conduct a pre-screening of retrofit design alternatives (1st step of the methodology developed in this work), and 2) to obtain benchmark data for comparison analysis between the novel methodology developed in this Ph.D. work and a methodology traditionally used in early stage process design. These publications were presented in 91st Annual Meeting of the Pulp and Paper Technical Association of Canada in Montreal (2009) and in The International Biorefinery Conference in Syracuse, USA (2009) respectively. The results indicate that production capacity can have a significant impact on the project profitability mainly due to potential capital cost savings with lower design capacities and the cost of feedstock. Moreover, the external uncertain factors can alter the project profitability substantially, and the ranking of design alternatives is therefore not unambiguous when considering the expected and the worst case scenario performance. The retained retrofit projects, based on both profitability and a risk measure, were then analysed using the capital appropriation methodology developed in this work.

The basis of this capital appropriation method, the cost modelling framework for manufacturing cost and pro-forma cash flow estimation, is elaborated in the article presented in Appendix C. The structure of the operations-driven cost model and its linkages to process simulation models and data available from information management systems are discussed and joint cost assignment methods are analysed with a set of example retrofit projects. All the retained retrofit design alternatives were analysed using this cost modelling framework and these results were presented in AIChE 2010 Annual Meeting in Salt Lake City, USA (Appendix G). In these two publications, the cost information obtained with the framework was further used to estimate retrofit project profitability, and on the other hand, to illustrate the cost-implications of retrofit projects and the impacts of production flexibility of one retrofit alternative on the margins of the facility.

The cost modelling framework was further expanded to evaluate pro-forma cash flows for long-term performance analysis of different capital spending strategies. The metrics of the financial performance and risk criteria that were identified and presented in the paper presented in Appendix E were implemented into this framework. These include short-term project metrics also used in the cost modelling framework papers (project profitability, project risk and cost impacts on P&P product manufacturing), and long-term metrics for business valuation (feedstock paying capability, capital performance, revenue basis renewal, and business risk). This paper also reports the results of the multi-criteria decision making using a case mill personnel-based panel and trade-off decision making method to weight the criteria.

Finally, the overall retrofit design methodology for capital appropriation, parts of which are discussed in detail in the other publications, is assembled into one publication (Appendix D). This reviews the major steps of the methodology, concretizing each step with the case study results.

4.3 Synthesis

This synthesis presents the main results of the work done in this Ph.D. in order to address the proposed methodology. The focus is on three critical aspects: 1) risk analysis in early stage retrofit design, 2) product costing and retrofit project cost-impact analysis, and 3) capital appropriation decision making. The methodology developed in this Ph.D. is also compared to traditional techno-economic analysis.

The case study results (absolute performance values) are not representative figures of the case study mill and company and should not be used in comparing the mill with other companies. Monetary values are presented in US dollars ($).

4.3.1 Risk analysis in early stage retrofit design

Multivariate stochastic analysis was applied in the large-block analysis (traditional techno-economic analysis) on all design alternatives at their low cost production capacity. Probability distributions for uncertain external factors that were identified using sensitivity analysis were assessed using publicly available data. Process-based and model uncertainties were excluded from this early stage analysis. This can be justified by the fact that the alternatives considered in capital appropriation for technology implementation (this does not include research and development projects) need to be already at a higher technological development level and process-based and model uncertainties need to be relatively low. Moreover, the markets for the products should exist to be able to commence the installation project in the near future. Thus, alternatives requiring a significant amount of development (e.g. several process steps to be proven at a large scale, or the overall system to be proven at demonstration scale, or markets to be developed) and processes that do not have guaranteed operation up-time are already screened-out in previous design stages that are not the focus of this work. This leads to a similar level of process–based uncertainty between all design scenarios at the time when they are evaluated using the methodology developed in this work. Furthermore, only uncorrelated distributions were used in the risk analysis. These distributions (including trend uncertainty for prices that have different annual inflation than the general price index, inflation and individual prices) are presented in Appendix I.

The risk of each retrofit scenario was assessed using Monte-Carlo analysis: a large number of cash flow series (5000 iterations, randomly selected values for uncertain variables) were calculated and the internal rate of return (IRR) and net present value (NPV) were evaluated for the series. The resulting profitability probability distributions are presented in Figures 1 and 2 in Appendix J. Based on these results some of the scenarios are not profitable under the economic assumptions, and they can be screened out. The measure of risk was selected to be downside project profitability (profitability obtained with 97.5% certainty or worst-case scenario profitability; this is an important metric in manufacturing industries according to Chadwell-

Hatfield, Goitein et al. (1996)), defined as the expected profitability minus 1.96 times standard deviation of the profitability. The list of most promising retrofit projects ranked based on statistically expected project profitability is shown in Table 4.1.

Table 4.1 Most promising design scenarios based on ranking using IRR

Feedstock, product (process)	**Capacity (ML/year)**	**IRR**	**standard deviation**	**Downside IRR**
Corn stover, Mixed alcohols (Steam reforming)	379	13.0 %	2.1 %	8.7 %
Lignin, Ethanol + higher alcohols (steam reforming)	189	12.3 %	2.0 %	8.2 %
Biomass, Mixed alcohols (Steam reforming)	95	8.7 %	1.6 %	5.5 %
Hemicelluloses, Ethanol + acetic acid (near-neutral VPP)	19	6.9 %	0.9 %	5.0 %
Biomass, Ethanol + higher alcohols (steam reforming)	95	5.9 %	1.5 %	2.9 %
Corn stover, Ethanol + higher alcohols (steam reforming)	379	3.4 %	2.0 %	-0.6 %
Pulp wood, Mixed alcohols (Steam reforming)	189	3.4 %	7.3 %	-11.1 %
Lignin, Ethanol + higher alcohols (gasification)	189	1.5 %	3.3 %	-5.1 %
Corn stover, Mixed alcohols (gasification)	379	0.7 %	3.4 %	-6.0 %
Biomass, F-T liquids (gasification)	95	0.6 %	2.1 %	-3.5 %

When comparing the ranking based on IRR and the relative risk of each of the retrofit projects (standard deviation -column), it is clear that the most promising alternatives are also more uncertain than some of the lower profitability projects. However, their downside IRR is superior to those of the less risky projects. Moreover, some of the projects have significantly higher risk although the same technology and products are considered. This results from different feedstock cost uncertainty.

In summary, even simple risk analysis using systematically quantified uncertainties can reveal important behaviours of the system. This knowledge can further be used in screening out higher risk retrofit scenarios in addition to low performance scenarios. Furthermore, in the case study analysis location specific cost and uncertainty data were used, thus the analysed concepts may perform differently in a different mill context and cannot be generalized.

4.3.2 Product costing and retrofit project cost-impact analysis

4.3.2.1 Development and application of the cost modelling framework

The structure of the cost model developed using the operations-driven costing framework described in 3.1.2 is illustrated in Figure 4.1. This structure is based on separate but strongly linked process and cost simulations. The data from the process simulation model(s) is passed to the driver and production rate matrices in the cost model through an interface (tool specific interface should be utilized if available for fast and reliable data transfer). Correspondingly, gathered market information (from mill specific contracts and the public domain) is used to define the price and price trend vectors and the probability density functions of price trends and prices. The facility's current and historical performance and required actions to keep the asset functional and improve its efficiency define historical and future fixed costs (FC) and capital spending into the pulp mill (required maintenance spending, depreciation, annual capital spending in development and replacements), and company practices in cost allocation define different allocation bases. These data define the corresponding data vectors in the cost model.

The cost model executes activities in a pre-defined calculation order and cascades costs further with all produced intermediates and products. The costs of a department are separated into variable and fixed costs, and these costs are then allocated to all cost-carrying products and updated in the intermediate cost tables or end-product cost table accordingly. Because energy is a key cost factor in P&P production, steam costs are defined in detail in the costing framework. The steam costs of each production activity are dependent on the cost of fuels used in the boilers (hog fuel, black liquor, fossil fuels). These fuel costs (for intermediate resources) can in turn also depend on the steam costs. Thus, the cost model has recycle loops that need to be solved iteratively. A simple substitution method was implemented in the cost model for obtaining a steady-state. Because the process simulation model is already in steady state and all drivers are known, this approach is sufficient for cost model convergence.

Capital cost estimates for the retrofit alternatives were constructed using publicly available data (biorefinery alternatives) and mill estimates (mill modernization). Investment costs and all historic and future capital spending were estimated at the department, or, activity level.

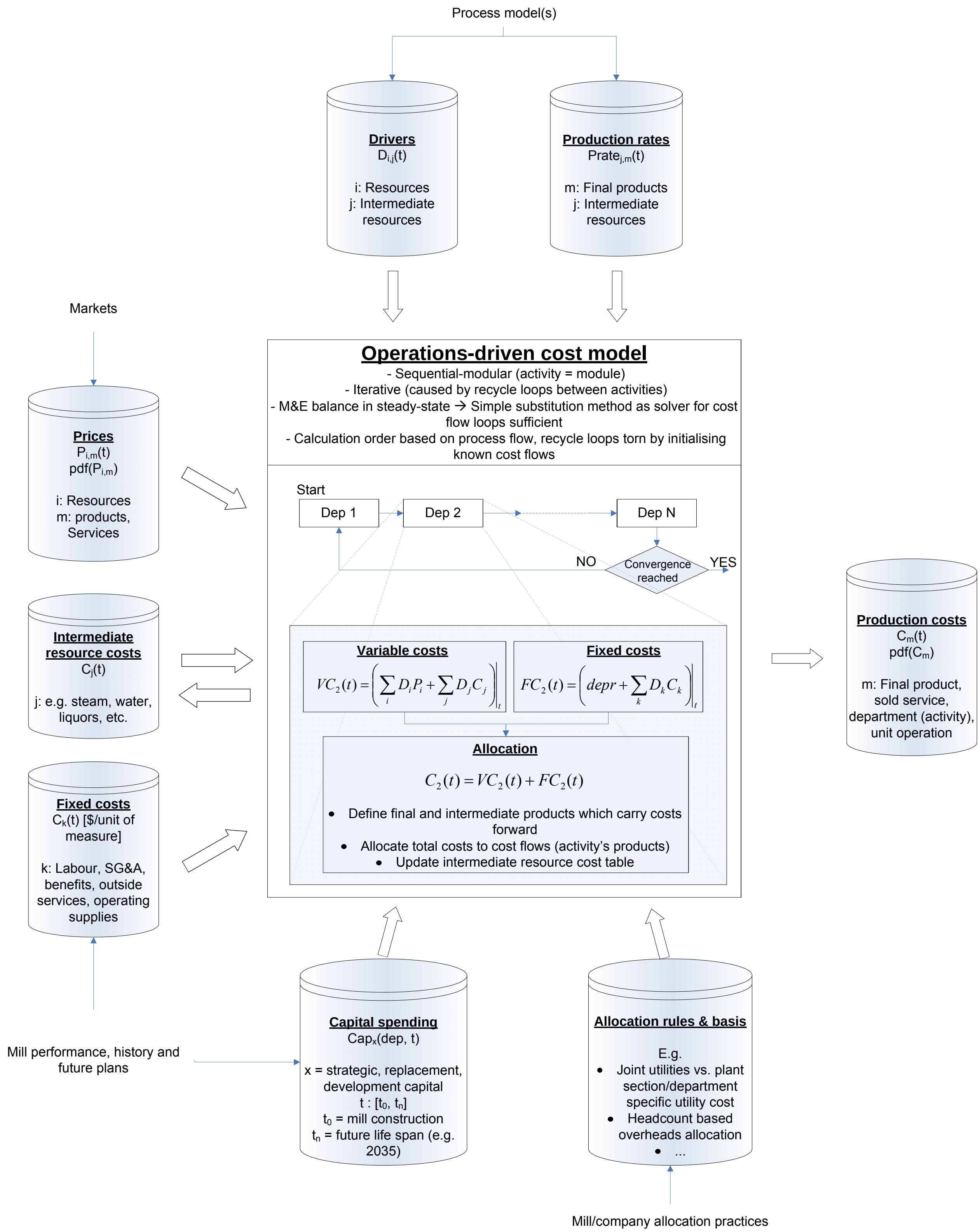


Figure 4.1 The structure of a cost model for retrofit capital appropriation

The cost model provides the production costs of all products. By comparing production costs of the core business product (pulp) between retrofit scenarios and the base case costs, the cost-impact is obtained (Figure 4.2). The base case production costs were validated using monthly statements from the same time period as was used for input data acquisition. The process simulation model was validated separately. The cost-impact (including all added costs or benefits realized at the paper mill that is integrated into the energy and water system of the pulp mill) varied between 0.2% increase and 19.2% decrease measured from the base case production costs. Thus, significant cost changes resulted from the retrofit projects consequently leading to substantial margins changes. The largest cost reduction was obtained for the simultaneous mill modernization and biorefinery implementation and both VPP scenarios. Thus, the mill modernisation project improves the biorefinery project cost reduction potential in general, resulting mainly from the additional capacity in all energy systems (boilers, turbines) and added electricity production due to better energy efficiency of the pulp mill.

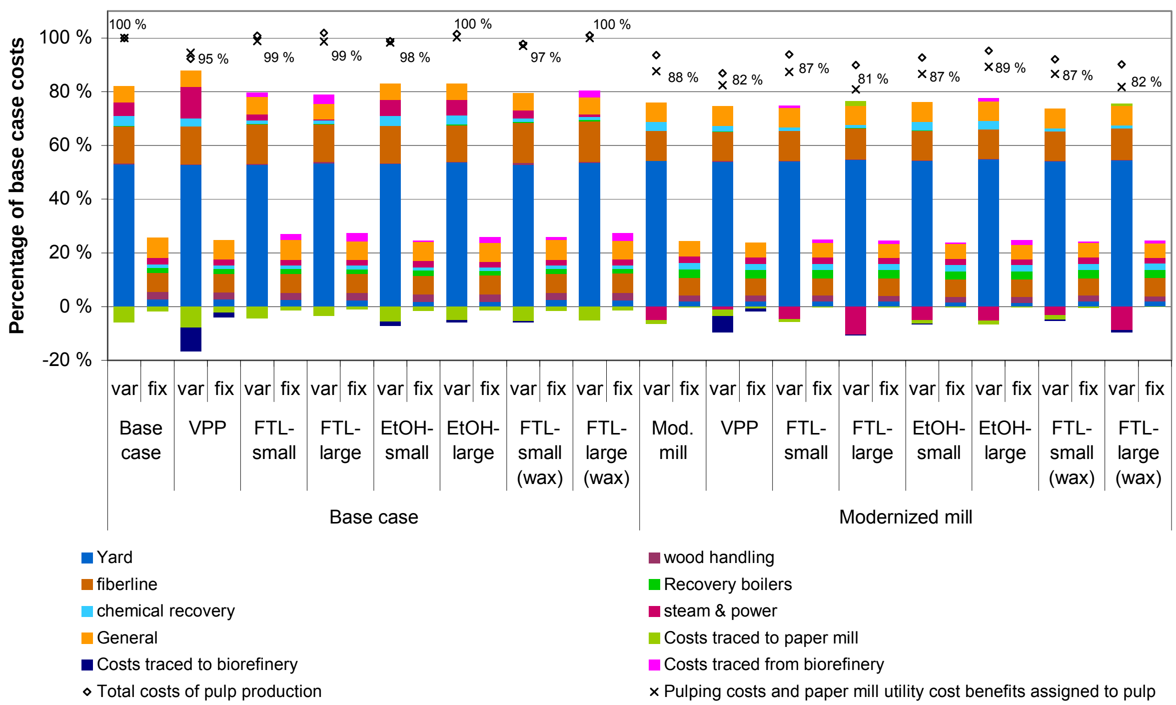


Figure 4.2 Pulp production costs in all retrofit scenarios

The bioproduct production costs in the same retrofit scenarios are shown in Figure 4.3. Although the feedstock costs are the main contributor to the total biofuel production costs, both the variable and fixed costs that are transferred between the pulp mill activities and the biorefinery activities impact significantly the total costs. In the VPP case, bioethanol production costs are significantly higher than in the other biorefinery cases, but the positive impact on pulping costs is at the same time much higher than in other scenarios. The high bioethanol production costs result from the cost assignment rules used in the calculation (chips and hemicellulose are valued to the same value) and high chemical costs for the pre-treatment.

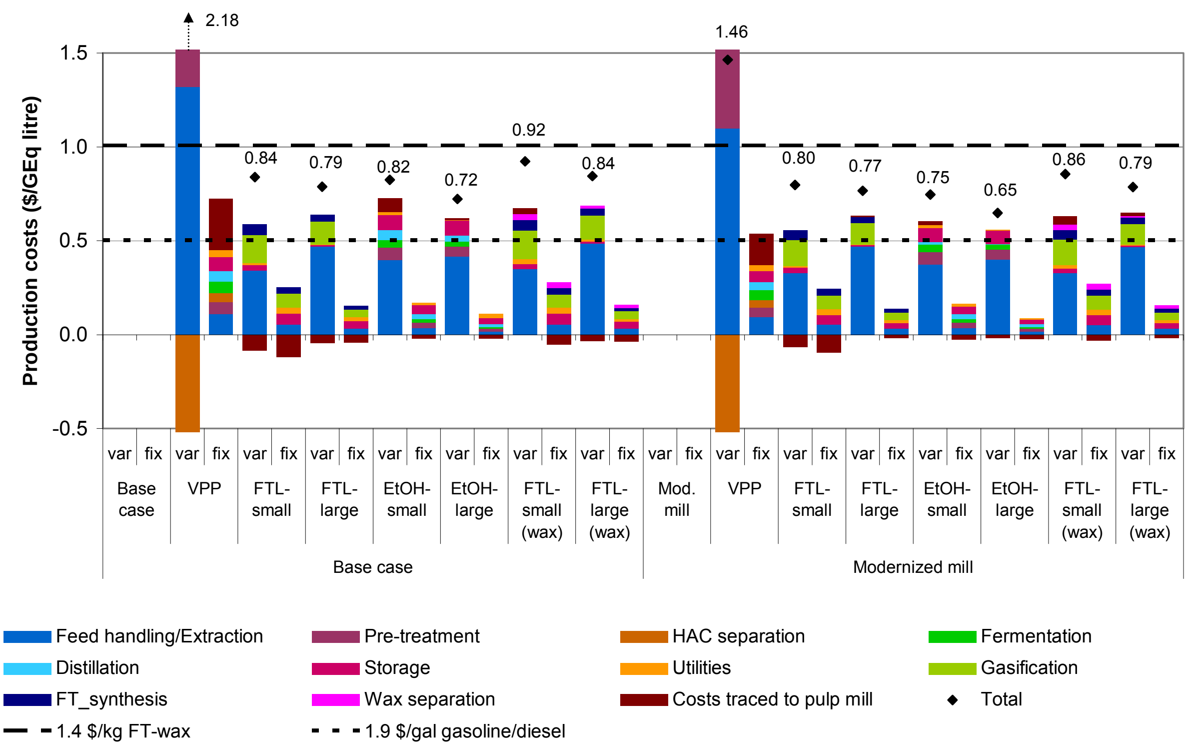


Figure 4.3 Bioproduct production costs in all retrofit scenarios

The energy cost changes constitute the main retrofit integration cost-impact. This can be seen in Figure 4.2 (lila bar) as steam & power department cost differences between retrofit scenarios, and it is elaborated in Figure 4.4 where the costs due to resource consumption and costs traced between steam & power department and biorefinery and pulp mill are included.

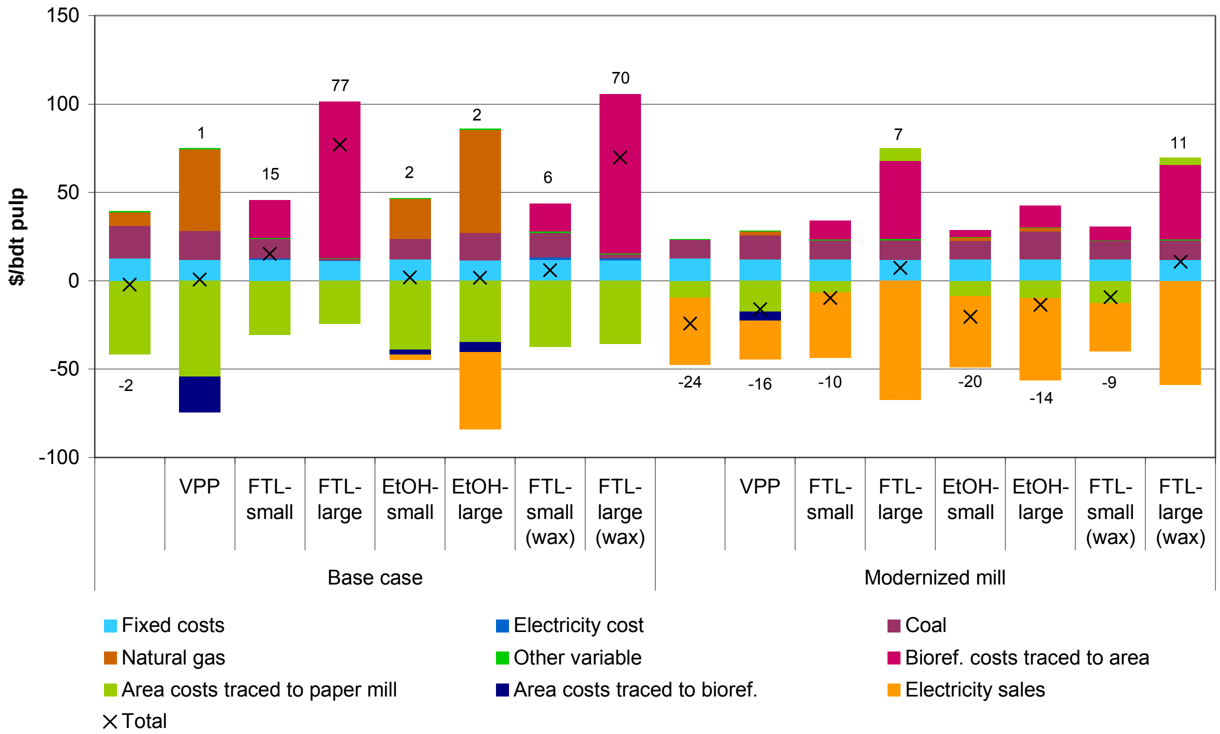
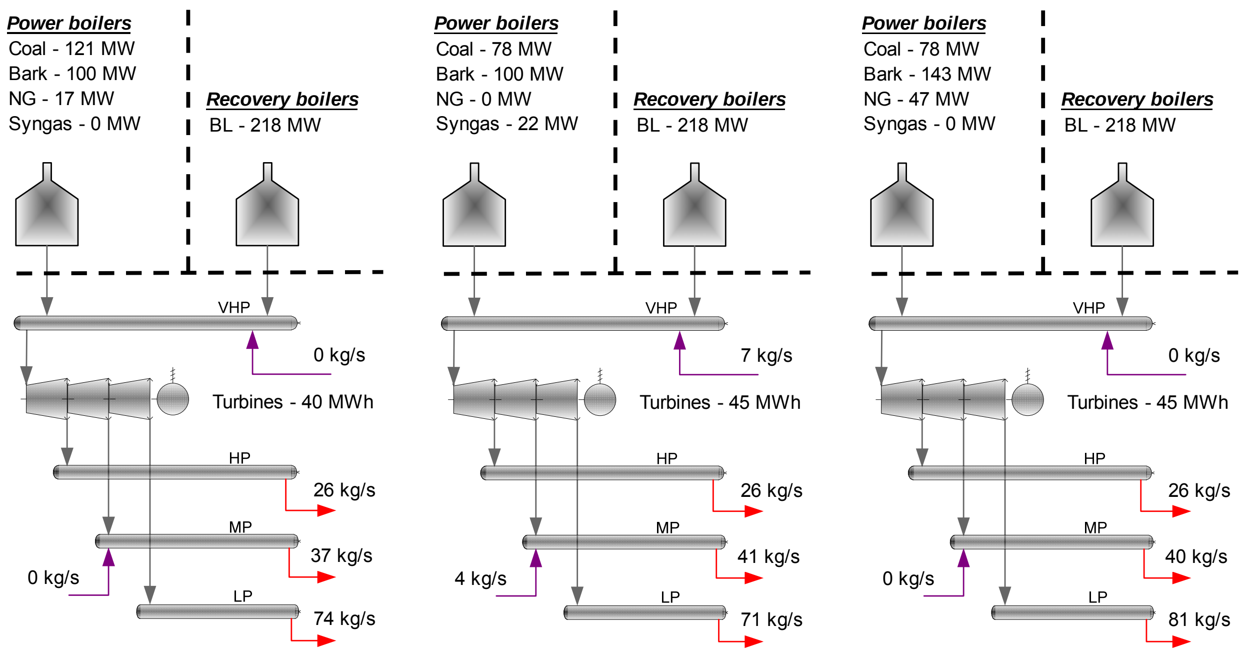


Figure 4.4 Steam & power department costs

Three factors, steam demand, available fuel mix and energy system constraints mainly define these costs. Figure 4.5 illustrates the two first factors in the base case, the small FTL process integrated into the base case, and the small corn stover-to-ethanol process integrated into the base case mill. In the base case, all boilers except the natural gas boiler are operating at their maximum fuel loads and the turbines have some excess capacity.

In the simulation of the energy system, electricity production is maximized while constraining the vented LP steam amount to the actual condenser capacity (a process simulator optimizer applying sequential quadratic programming (SQP) was used: Objective function: maximize electricity production; decision variables: turbine VHP steam flows, boiler fuel flows; constraints: boiler steam flow and fuel loads, turbine section flows, condenser flow, steam headers in overflow). After full utilisation of process residues (bark, biorefinery solid residues and tail-gas), the lowest cost fossil fuel (coal at the case mill) is used. Only in the case of higher steam demand and full coal/bark boiler capacity utilisation, natural gas is used. Different electricity production rates between design scenarios are the result of different MP and LP steam demands and system constraints: process steam is bled from the turbines and the turbine section capacities constrain the electricity production under changed demand even if the turbines are not run at maximum capacity.

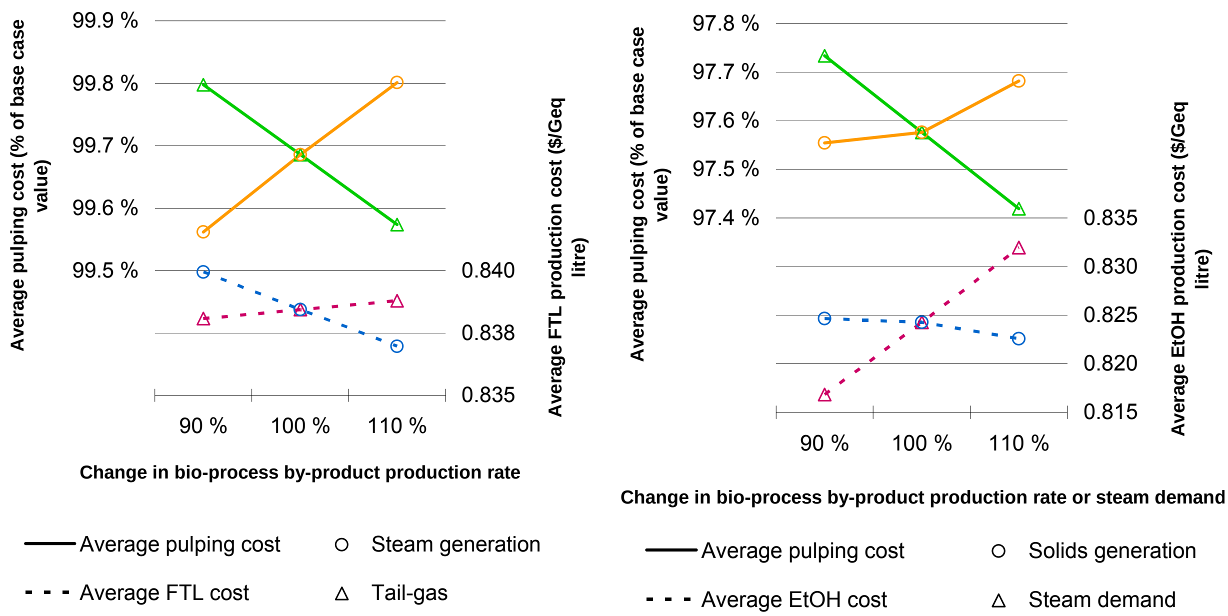
Although the steams and by-product wastes (solid biofuels such as evaporated distillation bottoms) are only intermediates, their price or production cost is explicitly defined in the intermediate resource costs table. The cost calculations are based on actual steam turbines at the mill with fixed steam loads (Smith and Varbanov 2005).



a) b) c)

Figure 4.5 Steam and power system of the case study in a) base case, b) FTL case, and c) corn stover-to-ethanol case.

Consequently, the uncertainties in the retrofit design assessment (process and model –based uncertainties at pre-feasibility level process design analysis), especially in the energy demand of the biorefinery concepts, by-product yield and energy content, and in the overall process models considering the energy system, have potentially significant influence on the retrofit cost-impacts. Moreover, these uncertainties can influence both the cost categories illustrated in Figure 4.4 and the steam and electricity costs of all other activities. As was stated earlier, in this work these uncertainties were not considered in the actual analysis, however from the cost-impact analysis validation standpoint the process uncertainties in two retrofit alternatives were studied. The influence of key energy related process variant uncertainties on the average pulp and biofuel production costs in designs illustrated in Figure 4.5 b) and c) are shown in Figure 4.6.



a) b)

Figure 4.6 Sensitivity of production costs on the energy consumption and by-product production rate of integrated biorefinery process, a) FTL case, and b) corn stover-to-ethanol case

The influence of 10% increase or decrease in any of the varied key energy-related process variants is clearly small on production costs although the energy cost changes mainly define the integration cost-impact magnitude. For instance, if the FTL process is not able to generate by-product steam as designed, the FBR can utilize coal to meet the steam demand, or if lower amount of energy is available from ethanol process solid by-product, natural gas can be used to supply the required heat. The cost-impact of these resulting changes in the fuel-mix are however not significant and thus, the obtained cost-impact results are not very sensitive to process-based uncertainties related to the energy integration of the biorefinery processes to the pulp mill. Moreover, the studies used as references in this work for the biorefinery process M&E balances are feasibility level design analyses done using rigorous process modelling and are therefore assumed to be reliable sources of process–related design information. In addition, the P&P process model was validated using process data to represent well the mill operations.

Joint utility cost assignment was assumed in the analyses. Using this basis, all utility consuming activities benefit or take losses when the total utility costs are changed. Choosing the joint cost assignment assumption is important for cost accounting because it has an impact on the costs of all products. Examples of this are shown in Figure 4.7 (pulp), Figure 4.8 (biofuel) and Figure 4.9 (fixed costs).

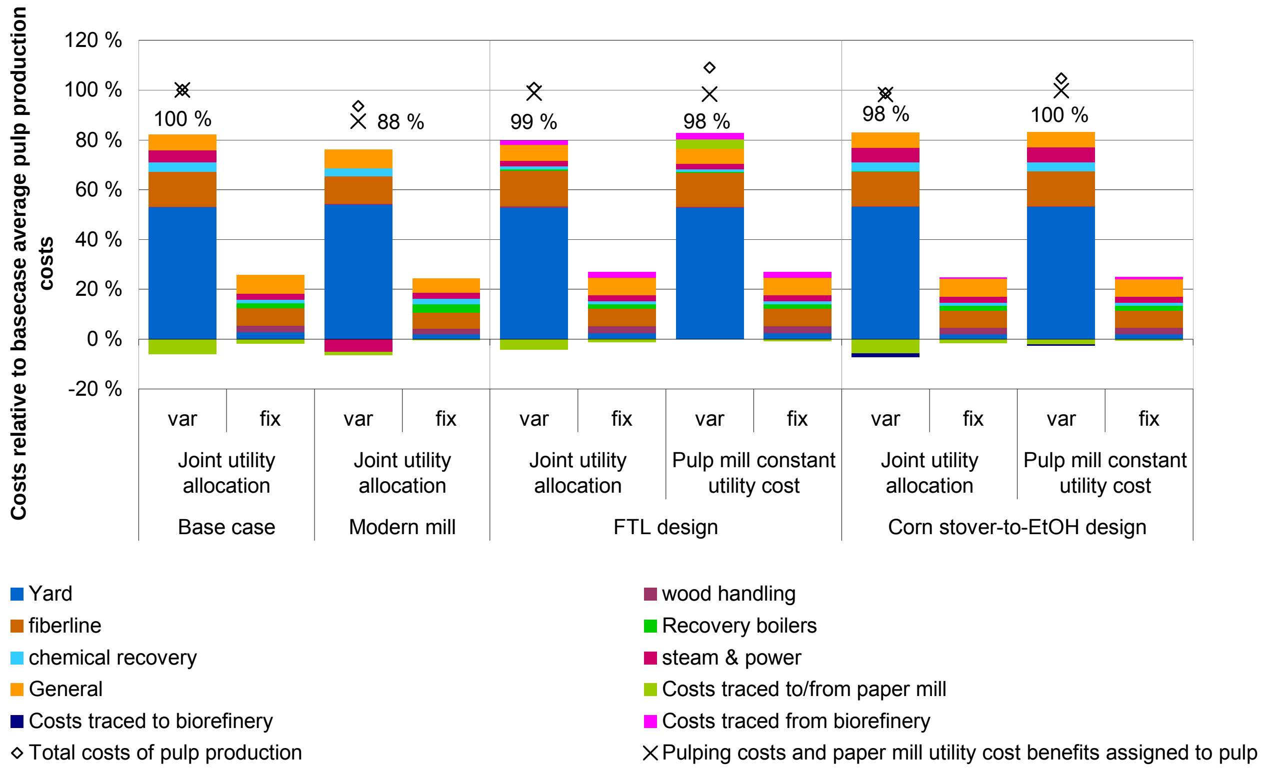


Figure 4.7 Impacts of the utility cost assignment basis on pulp manufacturing costs

Comparing the joint utility cost assignment to another assignment basis used in the P&P industry in which the pulp mill utility costs are kept constant and other utility consumers (in this case the paper mill and the biorefinery) absorb all utility cost changes, we can see a clear difference in pulp and bio-product production costs. This is mainly due to changes in the energy costs (steam demand and therefore fuel mix and electricity production potential) resulting from the biorefinery implementation.

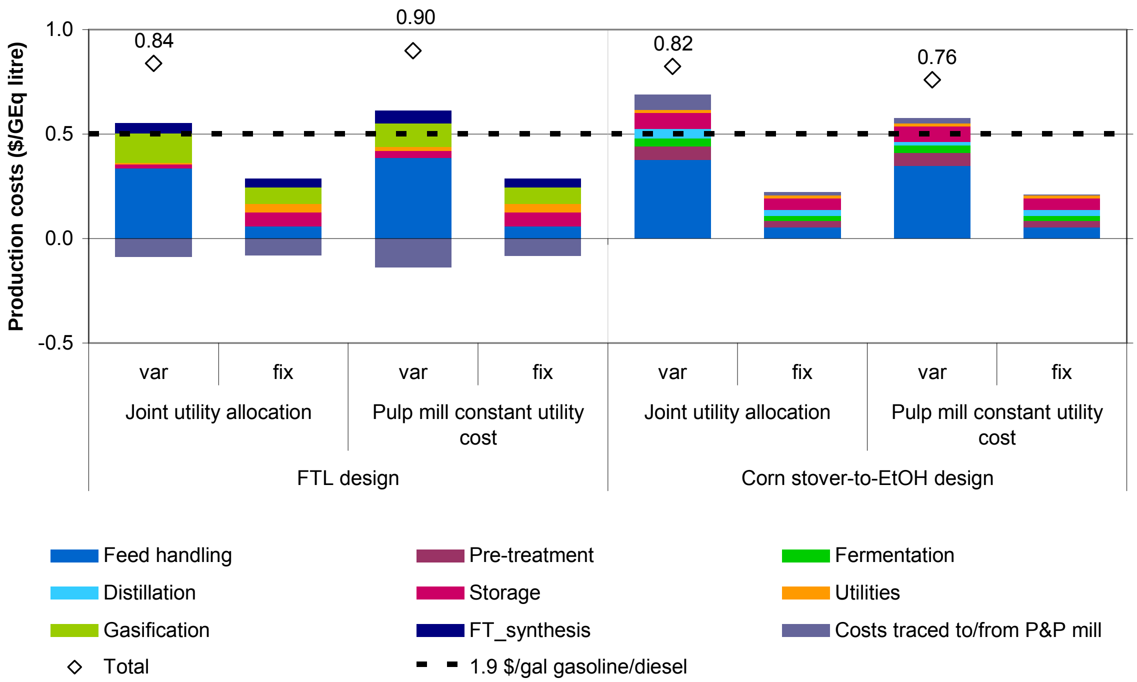


Figure 4.8 Impacts of the utility cost assignment basis on biofuel manufacturing costs

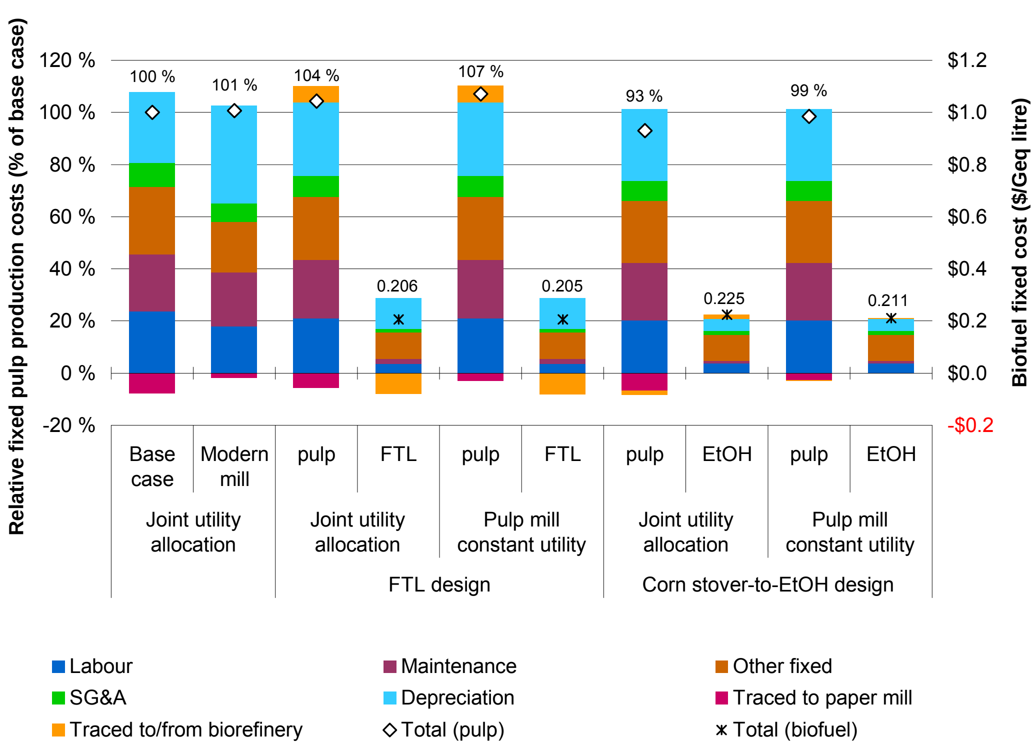


Figure 4.9 Impacts of the utility cost assignment basis on fixed costs

Depending on the biorefinery scenario, fixed costs are traced in either direction between the biorefinery and the pulp mill departments. This results from the assignment of intermediate resources such as process steam based on their consumption. Similarly, the fixed costs of these resources are assigned using the same driver basis.

Comparing the production costs to the traditional techno-economic analysis conducted on the same biorefinery design alternatives, significantly different results are obtained. In Table 4.2 the biofuel production costs in three example retrofit scenarios are compared.

Table 4.2 Comparison of traditional costing and operations-driven costing: Biofuel production costs in selected retrofit scenarios

Design scenario (integrated into base case mill)	Traditional analysis ($/Litre Geq)	Operations-driven cost analysis ($/Litre Geq) [3]
VPP	0.69	1.3
Small FTL process	0.59	0.77
Large corn stover-to-ethanol process	0.55	0.72

Major reasons for the differences lie in the assumptions that were used: In the traditional analysis, constant steam prices were assumed for all retrofit scenarios (only capital cost benefit was assumed for scenarios where no additional utility system capacity was needed). These steam prices were based on current marginal costs of steams at the mill. In addition, in the traditional study electricity production potential due to changed steam demand was fixed based on a simple conversion from the biorefinery steam demand without considering the actual system constraints and efficiencies. Due to these constraints in the case mill's energy system (boiler heat loads and steam turbines), these assumptions were overestimating the potential and therefore underestimating the production costs in the traditional analysis. Especially in the VPP case, increased steam demand needs to be supplied using NG which increases the energy costs at the

[3] Pulp & paper production cost benefits relative to the base case are assigned to biofuel production costs for commensurate comparison

mill significantly compared to the traditional analysis assumption of constant steam price. The second key difference in the assumptions was in labour costs. No additional workforce was assumed to be required in the traditional analysis whereas in the analysis using the developed costing framework, the available workforce at the mill was systematically assessed and extra labour was considered to be used when needed. Especially for the large corn stover-to-ethanol retrofit scenario, a significant amount of new labour is needed.

In summary, better transparency in costs and a systematic assessment of the cost drivers of the existing system in every design scenario is obtained when the developed costing framework is utilized. These cost models can further be used in pro-forma cash flow analysis and for obtaining a better understanding of the production system.

4.3.2.2 Marginal cost analysis and costs in volume flexible design

Decision making based on product margins is enabled when using the developed cost modelling framework. This is often needed for efficient marketing strategy execution, however, marginal production cost information used in operational decision making can potentially also be useful in strategic investment decision making. In Figure 4.10, the marginal and average pulp production costs, and average bioproduct production costs as a function of pulp production rate are shown for the base case, the small FTL and the small corn stover-to-ethanol design alternatives. Figure 4.11 illustrates the product profit margins and total margin in same design scenarios.

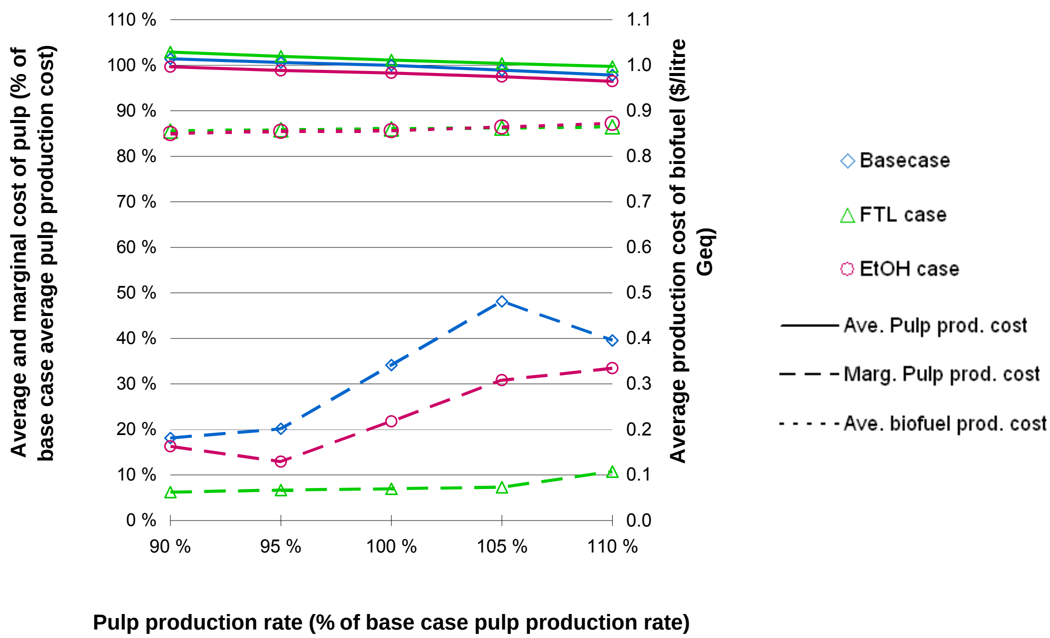


Figure 4.10 Average and marginal production costs of pulp and average biofuel production costs as function of pulp production rate in three example scenarios

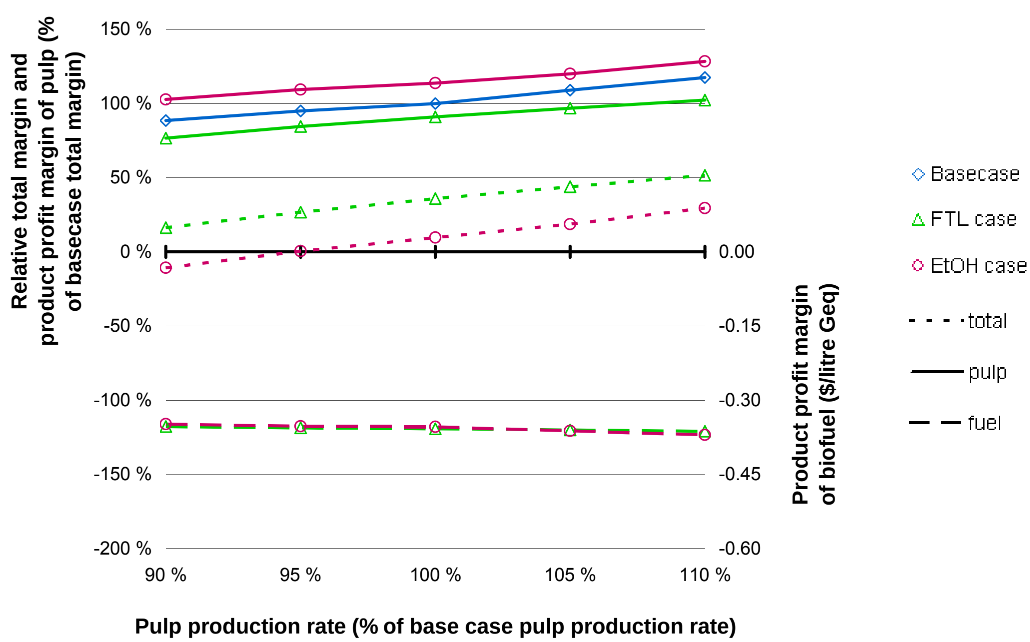


Figure 4.11 Total and product profit margins of three example scenarios as a function of pulp production rate

Varying pulp production rate has only a minor impact on the biofuel average production costs but a significant impact on the marginal pulping costs. Overall, in the FTL case the marginal pulping costs is lower compared to other scenarios. Moreover, marginal pulping cost has a local maximum at a production rate of 105% of the design capacity in the base case. This results from the energy cost change when the energy system is further stressed over its design capacity. The total margins and pulp product profit margin increase with increasing pulp production rate whereas the biofuel product profit margin decreases somewhat. This is also mainly a result of changed energy costs.

This kind of analysis is relevant for a pulp mill with variation in the order book of the products and volatile market prices. With the costing method developed in this work, the potential and the impacts of responding to these variations after different retrofit projects by increasing or decreasing pulp production can be assessed utilising marginal cost or the margins. However, operational metrics for strategic decision making were not included in this work.

Similarly, if the forest biorefinery processes are inherently flexible (shifting feedstock or an intermediate product between different end products is technically possible) the potential economic benefit of changing the production rate can be assessed. Figure 4.12 and Figure 4.13 demonstrate the cost impacts of such flexibility when the intermediate product synthesis gas is shifted between FTL production and combustion in the natural gas boiler to produce electricity.

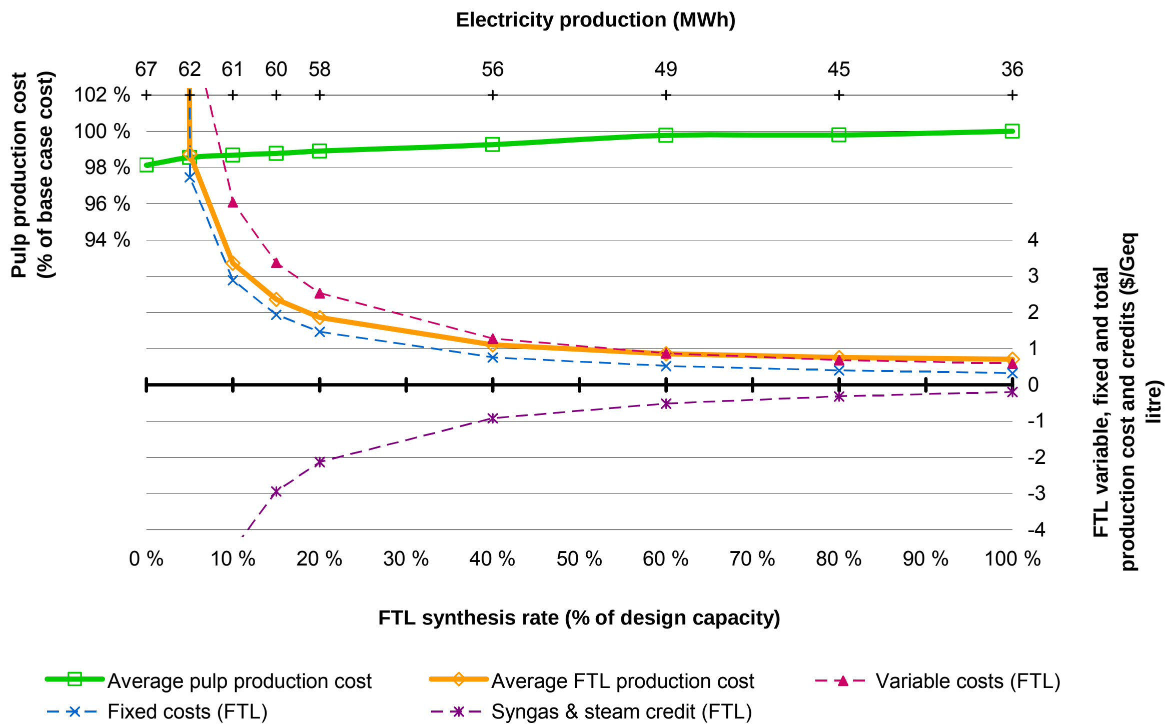


Figure 4.12 Production costs in FTL production system as function of FTL synthesis rate

FTL production costs are composed of variable and fixed costs and credits from synthesis gas and steam. These all decrease as the FT-synthesis rate increase. The design capacity is the lowest cost FTL production capacity. Pulp production costs at this lowest-cost FTL production rate are higher than at other production rates. These costs are a result of the utilization of the flexible production system: when more FT-liquids are synthesized, less electricity can be generated and both the pulp mill and FTL process have higher energy costs and thus, electricity price can affect the production costs of both products.

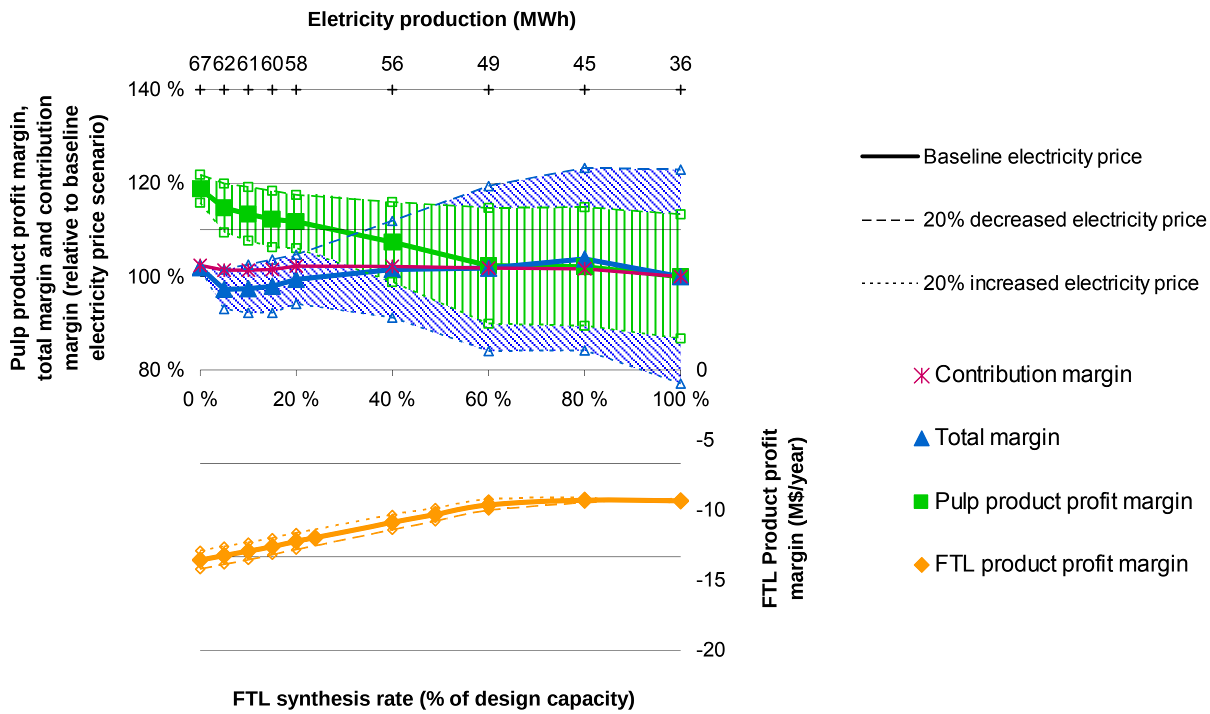


Figure 4.13 Sensitivity of product profit margins and the contribution margin on electricity price variation in varying FTL synthesis rate

Under different electricity price scenarios (shaded areas in Figure 4.13 depicts ±20% electricity price compared to base case price), the pulp product profit margins and total margin vary substantially. Because the FTL production requires a significant amount of electricity, a lower electricity price will enhance the margins.

In summary, cost information under different operating conditions of the system can be obtained in addition to product costs at design capacity. In a case when margins-based operational decision making is justified and a common practice, the marginal costs of all products can also be used to differentiate different strategic investments. This can aid selecting more responsive production systems.

4.3.2.3 Risk analysis using operations-driven cost analysis

With accurate operating cost analysis models, also the risk analysis becomes more reliable. The same approach was used to conduct risk analysis in the costing framework as was utilized in traditional techno-economic analysis. In stochastic multivariate analysis, the cost model is executed as a sub-task of the risk analysis method. The uncertain inputs (prices, drivers, trends etc.) are taken randomly from the probability distributions defined in the price tables. In Monte-Carlo analysis used in this work, the model is re-calculated N times with randomly selected input variable values to form output value probability distribution. As a result, all product costs (and intermediate resource costs) are obtained with a probability distribution and a statistical measure of dispersion (variance or standard deviation) can be calculated

In addition to external uncertainties considered in the large-block analysis, the uncertainty in pulp price and the capital cost estimate uncertainty were considered. The following assumptions were used to develop capital cost estimate uncertainty:

- Traditional retrofit projects use mature technological solutions and thus the capital cost estimate uncertainty results mainly from compatibility and thus installation cost estimate uncertainty
- Biorefinery processes are not technologically at the same level as traditional pulp mill technologies and therefore the capital investment cost estimates are more uncertain
- In pre-screening, technological maturity is considered as one basis for screening and at the capital appropriation level only technologies of similar uncertainty level are considered
- The cost estimate at the capital appropriation level is rarely significantly lower than actual project investment cost but underestimation is possible. Thus, the probability distribution should represent this behaviour

These assumptions lead to two types of probability distributions for the total project capital investment cost estimates. The Weibull distribution can represent the wanted features: cost estimate 95% confidence intervals of -10%... +15% for traditional and -15%... +25% for biorefinery project cost distributions[4].

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[4] traditional P&P mill retrofit project investment cost estimate – shape parameter 1.9, scale parameter 0.12 and shift 0.94; biorefinery projects – shape parameter 2.0, scale parameter 0.2 and shift 0.88

The results of the project risk analysis using the developed costing framework are discussed in 4.3.3.1 (Table 4.4).

4.3.3 Capital appropriation decision making

4.3.3.1 Mill-level evaluation of capital spending strategies

In addition to the project profitability used traditionally in process design techno-economic analysis, overall business- or facility-level capital investment scenario performance is measured in capital appropriation. It is done in order to be able to represent the opportunities and potential threats to the stakeholders of proceeding with each capital spending scenario. This performance evaluation incorporates all capital spending on the facility, expected efficiency and productivity improvements and revenues from all products instead of only considering one project separately.

Based on the cost model pro-forma cash flows including all relevant capital and operating costs, various financial metrics can be calculated for this purpose. Figure 4.14 illustrates the relationship between main cost factors and drivers (lowest branches of the tree) and some metrics used by different stakeholders to measure company performance.

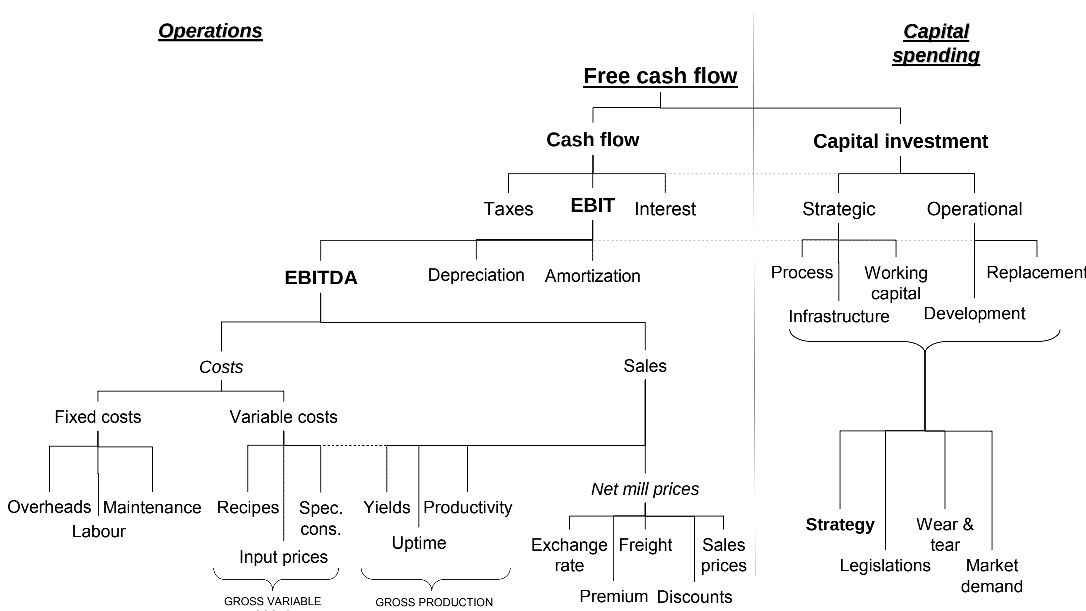

Figure 4.14 Factors affecting operational performance of a firm

For example, EBITDA (earnings before interest, taxes, depreciation and amortization), also called operating profit, measures the cash generation potential of the process usable for debt and interest payments (paid before taxes), and thus, it is used by new investors and creditors to evaluate their clients capability to pay debt. On the other hand, free cash flow (FCF) measures the net cash generated annually usable for reinvestments and dividends and is therefore an important measure for current owners. Similarly, mill and management evaluate operational and strategic project performance by using cash flow and investment cost estimates (after tax project profitability, or payback time).

Moreover, uncertainties in different cost factors, such as input prices (feedstocks, fuels, chemicals), sales prices and strategic capital investment costs can affect all these metrics and should be considered by the stakeholders.

A set of mutually preference independent, pertinent criteria in the context of competing strategic capital investment alternatives and metrics for these criteria were identified. This was done based on the expected key performance factors of forest biorefinery operations, the understanding of significant sources of uncertainty and the factors the stakeholders evaluate when approving capital to be used in large strategic investments. The set of criteria is listed in Table 4.3.

Table 4.3 Definition of the set of decision making criteria

	Definition of Criteria (measure)	**Justification**
1	*Project profitability* Expected risk-free project profitability (IRR)	Traditional capital allocation method which is commonly used as a screening metric. Using expected future trends makes this criterion realistically consider the most probable future returns.
2	*Project risk* Worst-case scenario project profitability based on Monte-Carlo analysis (Downside IRR)	Worst-case scenario profitability indicates what is the combined sensitivity of project performance on all uncertain market variables and project capital cost estimate. Capital cost estimation uncertainty captures the basic difference between known P&P process technologies and developing biorefinery process technologies.
3	*Core business benefit* Decrease in core product production costs ($\Delta C_{P\&P}$)	An indication of how well the project implementation will help in the short term to stay competitive with P&P products is an important measure, especially for mills struggling with high costs and significant integration potential. In addition, measuring the potential, rapidly realizable added cost benefits from the pulp & paper production can help margins-based P&P business operation.
4	*Feedstock paying capability* Ability to pay more for raw material (EBITDA/bdt biomass)	The feedstock costs take a significant share of all production costs, and future competition of bio-based feedstocks is going to change the raw material prices. A high amount of cash generated from operations that can be used for absorbing the possibly fast and significantly increasing raw material costs is therefore of significant importance to be able to stay operational in the longer term.
5	*Capital efficiency* Return on the capital spent in the assets (ROCE)	The overall asset performance considering all past capital spending on a fixed asset can be used to track the development of capital spending in time. Measurement of the asset's ability to make money is an important indicator of the asset's health for the investors, considering P&P industry's high capital intensity (Forbes 2000)
6	*Revenue diversification* Ability to absorb changes in product markets (fraction of bio-product revenue from total revenue)	A more diversified revenue basis is better able to absorb price variations in one or more products in the portfolio. Moreover, non-correlated products can better mitigate price volatility related risk.
7	*Business risk* Capability to react to business environment changes in long term in the capital spending scenario (Σ FCF)	The capability to respond to unexpected drastic changes in the business environment, such as significantly lower demand of products or new regulations, by re-investments and new strategic investments is an important indication of the risk in the business model for investors.

The performance of the retained design alternatives measured using these criteria (the formulae for all criteria are described in Appendix K) are presented in Table 4.4 and Table 4.5. The absolute performance values are not representative figures of the case study mill and company because of their strong dependency on the analysis boundary and assumed end-product prices[5]. The first three criteria (Table 4.4) are directly measuring the project performance whereas the last four criteria (Table 4.5) measure the investment strategy and its implications at the mill-level.

Table 4.4 Project level criteria performance of retained capital investment alternatives

Retrofit design alternative		Project profitability, IRR [%]	Project risk, downside IRR [%]	Cost reduction [$/bdt]
Base case		0 %	0 %	0
	VPP	0 %	0 %	29
	FTL-small	8 %	2 %	6
	FTL-large	0 %	0 %	7
	EtOH-small	0 %	0 %	9
	EtOH-large	0 %	0 %	-1
	FTL-small (wax)	12 %	9 %	16
	FTL-large (wax)	10 %	6 %	0
Modernized mill		3 %	0 %	67
	VPP	5 %	2 %	95
	FTL-small	6 %	3 %	68
	FTL-large	4 %	0 %	103
	EtOH-small	0 %	0 %	72
	EtOH-large	0 %	0 %	58
	FTL-small (wax)	7 %	5 %	72
	FTL-large (wax)	12 %	10 %	98

[5] In the case study, the analysis boundary was set to include only the pulp mill and the biorefinery processes and not the paper mill integrated into the pulp mill. The P&P mill end-product was therefore pulp which was assumed to be sold at an adjusted market pulp price (80% of market price), even although it is not currently sold to the market. In addition, not all the fixed assets related to the paper mill were included in the analysis.

Low or very low project profitability values, and therefore also the project risk values, were set to zero. This is done in order to obtain good normalization for decision making: the internal rate of return calculation from cash flow series changing sign several times has several solutions. In addition, highly negative cash flow series do not have a solution for IRR. Thus, highly negative values would potentially distort the decision making. Giving these scenarios a zero IRR and downside IRR value is also justified because these projects show a performance lower than any acceptable project would have.

Differences in project-level performance and downside performance values between more detailed costing analysis and the traditional techno-economic analysis (shown in Table 4.1) are evident from the production cost comparison of Table 4.2. These performance differences mainly originate from the energy cost analysis: rigorous calculation of the energy consumption using process simulation, and the future P&P mill energy efficiency improvements defined in the detailed cost models lead to lower total production costs in later production years compared to the traditional techno-economic analysis assuming fixed M&E balances over the analysis time period. Moreover, the increased returns from pulp manufacturing (difference between cost savings and sales price of pulp) enhances the overall profitability obtained when using the methodology developed in this work compared to the traditional analysis with no impacts on pulp profits.

More important than the absolute values are the changes in the ranking of the retained designs: Small FTL process profitability and downside profitability exceeded the ones obtained using traditional techno-economic analysis. This results from the significantly different energy costs from those assumed in traditional analysis (marginal cost of steam based on current system). This is illustrated in Figure 4.2 by the steam & power –activity costs.

The downside project profitability is also improved in the case of small FTL design. This results also from the same reason as the overall improvement: the actual fossil fuel demand (based on process modelling), and therefore uncertainty due to uncertain fossil fuel prices, is lower than the estimate done in the traditional techno-economic analysis.

In conclusion, the risk analysis due to rigorous costing is further enhanced from the traditional project techno-economic analysis by the decreased uncertainty in process and cost-impacts of retrofit projects.

Table 4.5 Mill level criteria performance of retained capital investment alternatives

		Operating performance, EBITDA/t BR feedstock [$/bdt]	Capital efficiency, ROCE [%]	Revenue diversification [%]	Business risk, FCF-sum [M$]
Base case		0	11 %	0 %	232
	VPP	-1	9 %	9 %	146
	FTL-small	47	9 %	10 %	191
	FTL-large	17	5 %	31 %	12
	EtOH-small	-10	7 %	12 %	143
	EtOH-large	0	3 %	37 %	-41
	FTL-small (wax)	75	10 %	16 %	209
	FTL-large (wax)	52	10 %	46 %	184
Modernized mill		22	11 %	6 %	137
	VPP	25	11 %	12 %	55
	FTL-small	185	10 %	12 %	103
	FTL-large	61	9 %	31 %	7
	EtOH-small	151	10 %	14 %	78
	EtOH-large	47	9 %	31 %	24
	FTL-small (wax)	209	11 %	16 %	118
	FTL-large (wax)	102	13 %	42 %	216

As is observed from Table 4.5, under the expected price scenarios and assumed production related variables (yields, reliability, energy efficiency, productivity, and their future improvement), the cash generated from operations in different capital investment scenarios results in different capability to respond to feedstock price changes. Mill modernization can enhance the feedstock paying capability of the implemented biorefinery. Because of the relatively low profits from biofuels production, the capital performance of the asset measured using return on capital employed (ROCE) is not improved from that of the base case mill.

Increasing production volume of the bioproduct and higher unit price of the bio-product increases the relative share of the revenues from those products. Thus, a large facility producing highest price product (FTL waxes), and on the other hand all large scale production with additional electricity production show highest revenue basis renewal.

Future performance improvements of the pulp mill are not able to overcome alone the product price erosion and the increasing costs. This trend is similar in all scenarios, however better overall performance can increase the total free cash flow generated in long-term. This free cash flow can be re- invested in the facility or paid to shareholders as dividends. Base case has one of the highest FCF-sum values among the alternatives because strategic capital investment is not needed. However, higher risk of equipment failures exist in this scenario and these can result in unexpected production breaks. This same applies to all FBR scenarios that are retrofitted from the base case mill. This risk is mitigated in the analysis by higher annual capital expenditures in equipment replacements and maintenance compared to the modernized mill –base scenarios.

4.3.3.2 Multi-criteria decision making panel

A panel of eight people from the case mill (mill manager, process engineers, R&D and strategic planning personnel) was assembled for an MCDM session. In the decision making context, considering the boundaries of the criteria, the panellists assessed trade-offs between most important criterion and all other criteria. Boundaries were the minimum and maximum of a criterion among the alternatives. In the case of project performance and worst case performance the minimum was set to zero. These trade-offs were assumed to be valid through the ranges of attribute values, because the criteria are mutually preference independent. Furthermore, the utility functions were assumed to be linear between the boundaries, reflecting risk-neutrality of the decision making panel. The applied trade-off method yields criteria weights as average of the panel preferences, and the standard deviation of the weights (Table 4.6). The standard deviation is a result of sensitivity analysis where the individual criteria trade-offs by the panellists were given the best fitting probability distributions. It was assumed that the trade-offs were non-correlated and a Monte-Carlo analysis was conducted to obtain the weight probability distributions.

Table 4.6 MCDM panel weights and consensus among the panellists

Ranking	Criterion	Weight (%)	Standard deviation (%)
1	Project risk	48.3	6.8
2	Project profitability	16.3	10.0
3	Cost reduction	11.0	2.9
4	Operating performance	10.8	5.0
5	Revenue diversification	10.5	3.7
6	Business risk	1.9	2.4
7	Capital efficiency	1.2	1.2

The weights clearly indicate the importance of short-term criteria in this decision making context for the case mill panel members. Extremely important to the panellists was the worst-case scenario project performance. On the other hand, capital efficiency as a decision making criterion was not seen as important, partly because of the company practices. Moreover, even though selected in unison, the most important criterion has a relatively high standard deviation resulting from Monte-Carlo analysis: the sum of the weights is normalized to unity in all Monte-Carlo iterations. This also results in weight distribution of the project risk criterion.

The ranking of the retained capital spending scenarios based on average overall utility values is presented in Figure 4.15 where the impact of the individual criteria (weight and its attribute intensity) are observed as the height of the parts of the histogram. The most important criterion (project risk) clearly dominates the ranking, however the impact of other attributes also effects the ranking. On the one hand, between the well performing alternatives a more balanced decision is obtained (all criteria are present in the overall utility) where overall ranking almost follows the ranking based on project-based criteria, except in the case of 3rd and 4th most preferred alternatives where good performance of 3rd alternative is emphasized by the good strategic performance. This good performance is due to very good feedstock paying capability of the 3rd alternative. This is mainly due to superior feedstock paying capability of the small scale FT-wax production compared to large scale production when feedstock costs are increased substantially. On the other hand, for the lower ranked alternatives that do not have as well balanced overall utilities, differences between the impacts of individual strategic criteria on overall utility and ranking exist. For example, the base case is not the worst alternative among the studied scenarios due to its lower capital investment requirement compared to all retrofit alternatives.

The lower boundary selection for the project profitability and project risk criteria (IRR is 0% and downside IRR is 0% for poorly performing projects and for projects with cash flows changing sign several times) causes the utility balance. These both criteria have zero values in the lower ranked alternatives (see Table 4.4). Therefore, the overall utility balance of these alternatives is somewhat “artificial” and the ranking between them might not be correct. Because the trade-off values are assumed valid through the range of possible attribute values, setting the lower boundary does not change the relative order of the alternatives according to those criteria. For example, an alternative having positive IRR will always have relatively bigger impact on overall utility from the IRR than an alternative having negative IRR. Thus, setting the boundary to zero does not impact the ranking between the alternatives having positive and zero impacts from these criteria, only all alternatives having negative impact are considered the same. Overall, these alternatives do not perform well, and the exact ranking between them is not the goal of investment decision making[6].

[6] This was tested with actual negative project performance values.

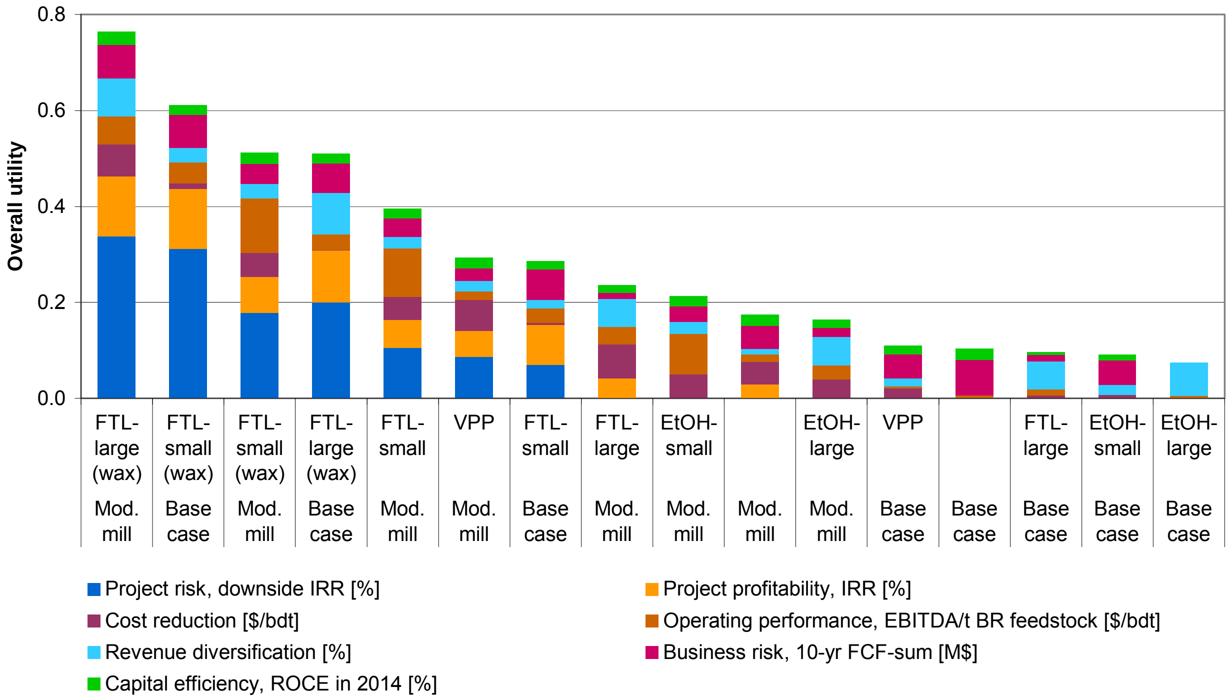

Figure 4.15 Ranking of capital investment scenarios based on overall utility value

The sensitivity of the final ranking of the capital investment alternatives relative to the panel member preferences is illustrated in Figure 4.16. The uncertain independent variables of the Monte-Carlo analysis are the panel trade-off values that are assumed to be normally distributed around the average. In general, the expected ranking is not changed due to the dispersion in opinion of the panellists. However, it is clearly seen that the alternatives where retrofit is done on the base case mill are more sensitive than alternatives with co-current mill modernization. These also lead to changes in the ranking illustrated in the figure.

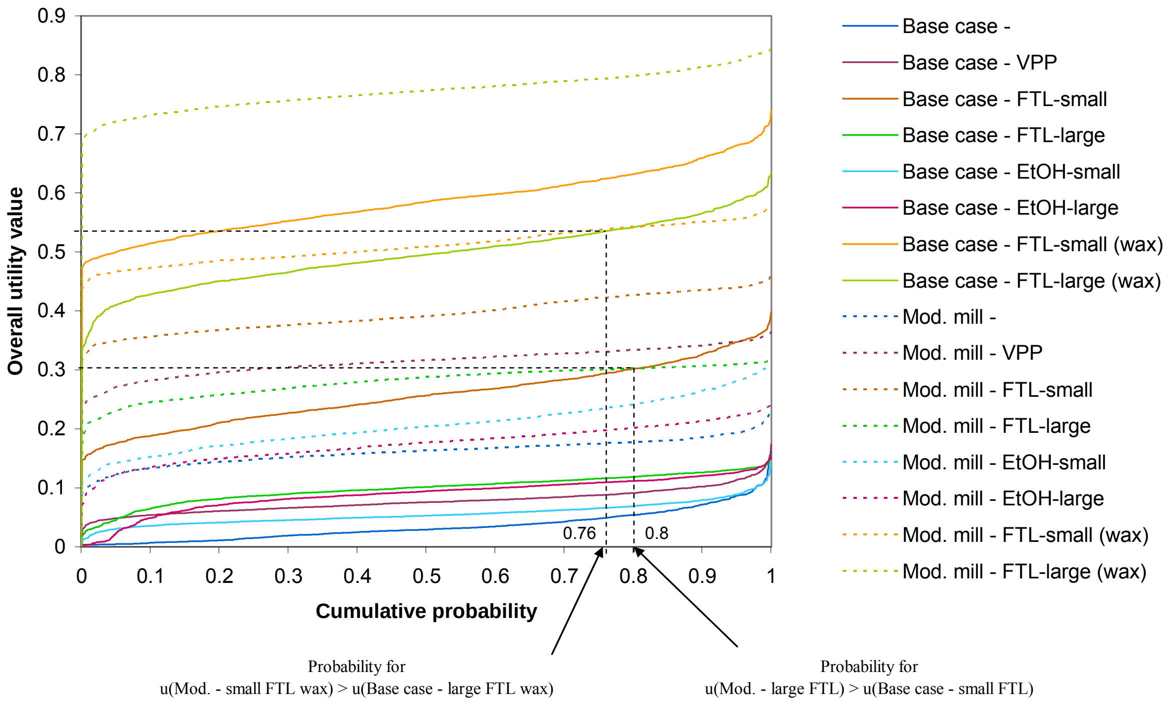

Figure 4.16 Sensitivity analysis of ranking

It can be argued that measuring only project-level criteria is sufficient for the ranking and decision making. On the other hand, the ranking of the 3rd and 4th most preferred alternatives is also dependent on the long-term criteria performance to a significant extent. Moreover, because of their differing attribute intensity and different uncertainty in the weights, this relative ranking occurs with 76% certainty.

Based on the sensitivity analysis, it is thus justifiable to cluster the alternatives to most promising and less promising capital investment scenarios, FT-wax production alternatives being the most promising options for the case mill. As was discussed above, the lower boundary selection can possibly change the ranking between the lower ranked alternatives and therefore also the cumulative probability curves of their overall utility may overlap differently and change their relative order.

4.3.4 Conclusions

In this chapter, the development of an analysis framework implementing the design methodology, and its application on screening and selection of strategic capital investment scenarios for a forest biorefinery was discussed. First, the use of multivariate stochastic risk analysis in traditional techno-economic analysis for more systematic screening of potential retrofit biorefinery implementation projects in a case study was demonstrated. A measure of financial project risk, worst case scenario project profitability, was utilized in parallel with expected project performance in the screening. Then, process-based techno-economic analysis implementation in management cost accounting that is based on activity-based costing principles was described and results of this analysis applied in the retained design alternatives in the case study were illustrated. The focus was on definition and evaluation of cost-impacts of retrofit process integration for better cost transparency in design analysis. Next, the cost analysis framework extension to pro-forma cash flow analysis and financial performance measurement was described, specifically aiming at commensurate comparison of different types of strategic capital investments in the capital investment portfolio of a mill. Finally, the use of identified relevant financial and risk-based capital appropriation criteria evaluated using the costing framework was demonstrated. An expert panel-based multi-criteria decision making process for ranking the retained design alternatives for the mill's capital spending was presented.

The results of the case study application of the methodology show that systematic analysis of external uncertainties can provide important information about the worst-case scenario performance of the retrofit projects. When this is used with expected profitability in screening-out economically non-promising retrofit design alternatives, it enables an objective assessment of the uncertainties instead of using subjective scoring methods. Furthermore, analysis of the retained retrofit design alternatives using the developed costing framework clearly quantified the cost impacts of these retrofit projects. These impacts varied significantly between retrofit design alternatives, which would be observed through management accounting in the case of normal process design and capital appropriation process only for the selected project after it is implemented and operating. The change in the core business cost competitiveness is an important factor for producers of commodity P&P products. Moreover, using these short-term measures in parallel with long-term performance criteria in multi-criteria decision making resulted in a ranking of alternatives different from the case of using only project profitability. This ranking also represents the preferences of all the case mill–based decision making panel members well.

CHAPTER 5 GENERAL DISCUSSION

The capital intensity of the P&P industry and the technological solutions of many of the bioproduct production systems are important factors for forest biorefinery decision making. Moreover, the relatively low capital efficiency of the P&P industry compared to other capital intensive manufacturing industries also makes this industry non-attractive to investors (Forbes 2000), and can potentially hinder the implementation of the forest biorefinery.

This combined with the uncertainties in the business environment of the forest biorefinery makes it imperative to apply a systematic risk analysis and effective decision making process in capital investment decision making for the forest biorefinery. This can enhance the investment projects' fit to the organisational strategy and therefore improve the financial performance, and also the attractiveness of the company.

In many cases, the higher risk investment projects are expected to have higher returns, and thus, subjective scoring is often used when analysing economic performance of potential investment projects. Moreover, different scoring-based investment opportunity analyses including subjective risk terms (such as SWOT-analysis) are applied to account for technological and market uncertainties. Thus, risk analysis is recognized to be important but it is not explicitly and systematically considered in the decision making.

Similar to the importance of risk analysis in investment decision making, strategic fit of the investment projects is very important for larger investments (Chadwell-Hatfield, Goitein et al. 1996; Carr, Kolehmainen et al. 2010).

The aim of this work was therefore to develop a retrofit process design methodology serving better the capital investment decision making process in the case of retrofit biorefinery implementation into P&P industry. This methodology was designed to use existing analysis capabilities for more systematic comparison of investment opportunities, and on the other hand for better management of uncertainties. PSE, management accounting and decision making methods were combined in a novel manner to achieve this goal (Figure 3.1). The methodology was applied in a case study to demonstrate how this design methodology can enhance the strategic capital investment decision making process.

5.1 Risk analysis in early stage process design decision making

Risk analysis in the overall methodology was applied in two consecutive steps of the decision making process: pre-screening and detailed economic analysis. Multivariate stochastic analysis was selected as the tool in order to be able to account for both the variation and the probability distribution of variation in the assumptions and the results. Monte-Carlo analysis was used as the analysis method. Supporting this selection is the vast literature showing one of the highest implementation level of this method in the manufacturing industry among all available risk analysis methods. Other analysis methods providing faster calculation are also available, for example the law of error propagation could be implemented in such an analysis. Especially in the case when the models are linear and the probability distribution is not of interest, this method is very powerful.

The data gathering for any risk assessment considering long-term planning is challenging, and requires a multi-disciplinary approach. In this work the forecasting and the uncertainty in these forecasts were assessed using public domain data (forecasts and historical data extrapolated into the future if no forecasts were available). Thus, the goal of this work was not to develop forecasts and forecasting models of the business environment, but rather to demonstrate that when available this data can be used by the stakeholders for a better understanding and therefore better management of the risks in individual investment opportunities. Similarly, the selection of the most suitable risk analysis method was not in the focus of this work. Even computationally heavier methods are acceptable to achieve the goal of managing better the uncertainties in investment decision making.

The worst case –scenario project profitability (defined as expected profitability minus 1.96 times the standard deviation) has been used in the capital investment analysis. In addition to this statistical measure of risk, the resulting profitability probability distribution obtained using the overall methodology can illustrate the alternatives for the decision maker.

The risk analysis in early stage design screening is intended to measure relative uncertainty between the design alternatives considered in the study. The same applies to the statistically expected project performance, and thus these values are not necessarily comparable with other studies. Different assumptions behind the analyses regarding prices, inflation and analysis boundaries can lead to significantly different performance and risk analysis results. This also applies partly to the comparison between the large-block analysis step and the advanced costing step results: the analysis boundary was kept the same but the assumptions were changed from the large-block analysis simplifications regarding the integration impacts, resulting in shifting of profitability and worst case scenario profitability. Thus, the absolute project risk values cannot be directly compared, however the relative uncertainties are comparable.

The incorporation of uncertainties through cost uncertainties (products and feedstocks – price uncertainties, technological development stage – capital cost estimate uncertainty) enables accurate quantification of the overall risk. This is useful when financial measures are used for all decision making criteria, which in turn makes the criteria weighting in decision making easy to understand compared to the weighting involving different units for the measures (for example a comparison between a monetary measure of profitability and a nominal technological risk or market maturity score). Moreover, in capital appropriation decision making the goal is to select projects that are technologically proven and thus possible to be implemented in the near future. The decisions are not final and the next level in the design process can bring up new information that can alter the decision.

5.2 Product costing

The use of advanced costing methods, such as activity-based costing, has been studied in investment project analysis and process design. The expected benefits include the reasons for the application of these methods in cost accounting: better transparency in cost breakdown (division into resource costs at activity and unit level and per product instead of overall resource costs of production), systematic allocation of overhead costs and assignment of joint costs. The use of these methods in the analysis of new projects and new process designs however also has a disadvantage compared to cost accounting of operating facilities: the required data and knowledge is not readily available and thus methods to generate all needed information are needed.

To respond to this, in the developed cost modelling framework using activity-based costing principles, a separate but linked process modelling and simulation approach was chosen: plant-wide process simulation models of the process design alternatives were used to provide the needed driver intensities for the cost model. Drivers that are not based on material and energy flows were considered separately. In addition to being able to produce the required data, this approach benefits also the process design activity by providing only one process representation and one cost model for the design analysis.

The structure of the cost models was modified from that of the traditional activity-based costing by introducing a new resource category, intermediate resources. These are treated as real resources in every process activity or department consuming them, all activities producing or consuming these resources update their costs respectively. Cost flow between activities is through these intermediate resources rather than as a monetary cost flow. The benefits of this structure are easier addition of new design scenarios into the existing cost analysis and better transparency in inter-activity cost transfer (through simpler cost transfer structure). Furthermore, this is only possible when using a process simulation model in order to guarantee that no costs are generated or disappear. If data from an information management system is used, there is no guarantee that it is a steady state representation (all intermediate resources that are generated are also consumed) unless some form of data reconciliation using steady-state process simulation is used.

A potential benefit in addition to good product costing is the enabled costing under different demand and price scenarios. Marginal costing and standard full costing in different operating regimes and temporarily increased or decreased production of one or more products is possible. Even though this feature was not used in this work as strategic investment decision making criterion, it has potential in analysing the responsiveness of the investment strategies against a changing business environment, and, in designing the production capacity for retrofit designs.

Cost allocation and assignment in retrofit design in the P&P industry often follows the rules used currently. That is, the pulp mill operating normally enjoys fixed and low utility costs, whereas other consumers absorb the extra costs due to fuel mix changes and price variations. These costs are estimated for example by using total or marginal costs with the current demands. When the utility system load significantly changes due to the retrofit project both the total and the marginal costs are changed, and thus the assumption of constant utility costs may not be valid anymore. Using a joint or constant pulp mill utility cost assignment approach does not change the overall cost-impact of retrofit projects, however it enhances the understanding of the impact of the cost assignment basis selection.

5.3 Capital appropriation decision making

In the developed strategic investment decision making methodology two steps of decision making are used: pre-screening and multi-criteria decision making. This is similar to the decision making gates in the traditional capital investment analysis discussed in 2.5.1. Important implications of financial performance to all stakeholders and various uncertainties including project risk, feedstock paying capability and business risk were assessed in the second decision making step and utilized explicitly in decision making. This enables a systematic risk analysis instead of discounting the performance criteria for each retrofit alternative. In addition, the fit to company strategy and targets using commonly used measures for the criteria (capital efficiency, revenue diversification, project profitability) is guaranteed compared to the discounting approach where the expected (in non-statistical meaning) performances are lost with the discounting. Furthermore, with accurate cost accounting as the basis for the decision making and the comprehensive set of decision making criteria, the focus of the decision maker can be directed to establishing the attribute preferences instead of incorporating all relevant aspects of the decision making context into one criterion and its discount.

The case study weighting results show the importance of the short-term performance of strategic projects at the case mill. This can partly reflect the individual panellist roles in the corporation and the capital budgeting techniques preferred in the corporation. In addition, only when the decision making method becomes a common practice to the decision makers and the criteria are used constantly, a full appreciation of all criteria will be obtained and robust decision making is constantly achieved.

Application of an MCDM method in the capital investment decision making process encourages the systematic structuring of the underlying problem and therefore commensurate comparison of alternatives. To avoid unambiguous comparisons, the decision making criteria were considered at the same decision making level. This removed the need of aggregating the criteria (e.g. to long-term performance and short-term performance) which can be difficult due to the different units of each criterion. Moreover, there was also no need to compare such aggregated criteria, which is commonly seen in the decision making literature.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Contributions to the body of knowledge

A method for systematic incorporation and management of uncertainties in external design factors in the capital investment decision making process

- A more systematic representation of impacts of both short-term and long-term uncertainties (e.g. price variation and price trend correspondingly) on the financial decision making variables using Monte Carlo analysis at the large-block analysis and operations driven cost model-levels

- The uncertainty and ambiguity in overall facility performance due to the retrofit project implementation is mitigated and the effects of external uncertainties can be clearly addressed because the cost implications of integration are systematically addressed using process simulation and cost modelling. In addition, the facility specific productivity/efficiency improvements, and annual capital spending achieving these improvements at the department level are represented by activity drivers in the cost models.

Development and application of a costing method using activity-based costing principles, linked to M&E balance models for more rigorous integration impact analysis

- A novel activity-based cost model structure using intermediate resources to carry cost flow for better utilization of the mass and energy flow –basis of many of the inter-activity and cost object activity-drivers. This structure also enables easier development of the cost models of retrofit alternatives compared to conventional ABC

- Systematic analysis of impacts of integration on existing systems using a facility-wide process simulation model leading to a reliable mass and energy balance representation of the facility’s new steady-state

- Increased consistency between the M&E balance and cost analysis through the linked process and cost models, enabling a) the identification of process and financial variables that are most impacted by the retrofit projects and 2) quantification of the changes in the variables

- Realistic representation, and therefore better understanding of the changes in costs of common activities due to the retrofit project allowing better forecasting of the future performance of the core business

Systematic formulation of the link between long-term capital spending planning and process design analysis

- Systematic representation of the key capital appropriation criteria using operations-driven cost modelling based cash flows for realistic estimates of both project performance and company performance under the assumptions of the considered capital spending plan

- Utilisation of a set of economic and risk –based criteria that well reflect the requirements (project and strategic level), conditions (existing systems, developing processes vs. mature technologies) and environmental factors (core business price erosion, future competition of biomass, cost of energy) in retrofit design analysis. This enables better understanding of the retrofit project opportunities in the investment decision making process

- Utilisation of a panel –based MCDM-process to interpret and weigh multiple financial investment decision making criteria resulting in a rational decision from both project requirements' and company's performance viewpoint

A retrofit design methodology, enabling better capital investment decision making in a P&P company. The methodology is a combination of PSE tools, stochastic multivariate analysis, existing cost accounting methods and a group decision making method

- Combination of process simulation and operations-driven costing that are used in daily process analysis and facility operations planning and reporting results in a systematic and realistic representation of cost generation in the retrofitted facility

- Evaluation of financial performance of a pre-screened set of retrofit capital investment alternatives using the operations-driven costing framework as long-term cash flow source for financial data and project and strategic level financial performance measures

- Conducting a panel-based multi-criteria decision making (MCDM) process utilising economic-based performance and risk criteria for a rational decision that accounts for the values of key stakeholders

6.2 Future work

Overall methodology

The developed methodology targeted at aiding capital appropriation and it was constrained to consider one production facility. As was discussed by Komonen et al. (2006), at the facility level asset management strategy aims at a good fit with corporate asset management strategy but at the same time feeds information into the upper level strategic planning. Thus, when the methodology developed in this work would be adopted at every production facility of a company, the information of the performance of various capital appropriation alternatives could be utilized in the corporate strategic planning and asset management decision making.

Costing framework

The time horizon in the pro-forma cash flow analysis in the costing framework was discretized into one year periods. The cost model itself enables also shorter interval cash flow analysis, and the costing framework could be utilized in analyzing the potential impacts of operational decisions on financial performance of the facility in different capital investment scenarios. This was illustrated with two examples: marginal costs of production of pulp with varying pulp production rate, and costs of production in volume-flexible production system.

An efficient interface between the cost accounting tool and process simulator could further aid the cost analysis: especially marginal cost analysis requires systematic M&E balance calculation and utility system optimization. This, depending on the preferred objective function, should utilize the same input values as the cost model and potentially the results of the cost model (internal by-product costs), thus leading to an iterative solving-scheme of the two models. If the simulation infrastructure with efficient solvers is also equipped with an external calculation routine interface, the iterations required in the developed cost modelling can also be solved simultaneously with the process model.

Mill level capital spending scenario evaluation

Expansion of the current model to consider also operational capital investment projects might be of particular interest to older P&P mills: commensurate evaluation of all capital spending can enhance the asset management. This is readily enabled by the cost modelling framework: operational projects can be expressed in the process simulation models and in the mill performance efficiency factors that further reflect the project impacts on the costs. This implies also that potentially some additional decision making criteria should be introduced to the MCDM.

Decision making

The aim of choosing the decision making method for this study was to mimic a real decision making situation to maximum extent. Furthermore, the decision analysis relied on pre-defined assumptions about the risk attitudes of the decision makers and the boundary conditions of the attributes. The definition of these with decision makers, or utilization of other decision making methods could potentially enhance further the understanding of the decision maker of the problem.

Risk analysis in capital appropriation

The risk analysis in both the pre-screening and in the decision making steps included only external uncertainties (and capital cost estimate uncertainty). This was assumed to be a justified assumption in this decision making context: if a strategic investment is to be allotted capital, it needs to be at relatively high technological and market development levels. On the other hand, to be able to plan for the long-term, also alternatives earlier in the development pipeline should be included in the analysis and thus a means for incorporating the process-based uncertainties in the capital appropriation methodology could be implemented. In the developed costing framework, this distinction between strategies was only done between traditional mill retrofit projects and biorefinery projects through different capital cost estimate probability distributions.

Moreover, the inclusion of uncertainty in the process parameters could aid the capital appropriation risk analysis. This is possible if the process dependencies are well defined (process simulation models represent the process well in the operation window) which is the case for mass and energy balances. However for complex reaction systems such as bioreactors this is only possible if a sufficient amount of data is available and is most probably more relevant in feasibility level analysis of the retained design alternatives.

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APPENDIX A – Article: Integrating bioethanol production into an integrated kraft pulp and paper mill: Techno-economic assessment

Integrating Bioethanol Production into an Integrated Kraft Pulp and Paper Mill: Techno-Economic Assessment

By E. Hytönen and P.R. Stuart

Abstract: Both thermochemical and sugar process technologies can convert lignocellulosic raw materials into ethanol. To identify economically feasible solutions using these technologies, while the final decision should be based on a more extensive set of criteria, simple after-tax Internal Rate of Return (IRR) can be used as a selection criterion. In this paper, several integrated forest biorefinery design alternatives have been evaluated for an integrated kraft pulp and paper mill.

Based on prices and raw material availability, as well as published information about biorefinery processes, it was clear in this particular case study that corn ethanol is the most feasible option. It provides an IRR of over 20% at larger plant capacities. Following the corn ethanol option, thermochemical mixed alcohol synthesis routes also have interesting economics.

Although fossil-based transportation fuel prices have plunged quickly after having skyrocketed during 2008, the environmental awareness and goals for fossil fuel use and emissions reduction have not been forgotten. Also, other aspects, such as energy security and the opportunity to increase revenues by manufacturing products based on biomass in general, continue to provide strong motivation. Forestry companies are seeking improved profits from the implementation of new and sustainable business models, and one serious strategy exploits the concept of biorefining.

Bioethanol production as a biorefinery objective is very popular. It is volume-wise the most produced bio-product in the world after pulp and paper products, and its demand is rising due in good part to government legislation and policies. The food-fuel dispute has led to increasing interest in lignocellulosic biorefineries, but in order to fulfil the demand using these feedstocks, new and existing technologies need to be further developed and integrated with existing ones.

One promising option is the integrated forest biorefinery (IFBR). The forest industry has access to the most abundant biomass resource. The IFBR can provide the forest industry both product portfolio diversification, and at the same time, reduced pulp and paper product production costs, to help companies survive the current difficult markets, and possibly even prosper into the future. Bioethanol, and other bioalcohols and biofuels, can subsequently be used as raw material for the production of value-added derivative bioproducts. This could be the next step for forest industry companies to further diversify their product portfolio and generate additional revenues.

This study focuses on assessing the profitability of bioethanol production using different process technologies. This enables the selection of promising ethanol production options, but does not consider the relative economic attractiveness of producing other biofuels and bioproducts.

To assess the production and capital investment costs of ethanol biorefineries, as well as the impacts on environment and the supply chain, process systems engineering (PSE) tools can be used. Tools such as process simulation cost modelling, life cycle assessment (LCA), and supply chain management (SCM) all have their place in the analysis of biorefinery implementation strategies. Since the economic aspects are in many cases the dominating final decision making criteria, systematic methods are needed to evaluate and compare different IFBR options to demonstrate to the forest industry and policy makers the profitability of biofuel production.

LITERATURE REVIEW

Raw material availability and cost plays a key role in high volume biofuel production. It varies significantly on a national and even on a regional level, and therefore biorefinery solutions are location-dependent. Perhaps the best known example of comprehensive raw material assessment is the "billion-ton vision" from the U.S. Department of Energy [1]. The data and other information used in this assessment are public and have been used in several state-level assessments that are useful for mill-level decision making in the U.S. [2, 3]. It has been recognized that raw material cost is an important factor in biorefining. "Process improvement invariably makes the cost of raw material the dominant factor in overall refinery economics" is

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TABLE I. Raw material definition.

Code	Raw material
B	Woody biomass: energy wood, bark, logging slash, undesirable trees, thinnings and forest debris
P	Pulpwood (hardwood)
H	Hemicelluloses extracted from pulpwood
L	Lignin separated from pulpwood
C	Corn
CS	Corn stover
FW	Food processing waste: brewer grains and whey from the dairy industry

TABLE II. Thermochemical ethanol production routes.

T1	Gasification, MA synthesis, ethanol separation
T2	Gasification, syngas fermentation, ethanol purification
T3	Steam reforming, MA synthesis, ethanol separation
T4	Steam reforming, syngas fermentation, ethanol purification

TABLE III. General sugar platform ethanol production routes.

S1	Acid hydrolysis, fermentation, ethanol purification
S2	Pre-treatment, enzymatic hydrolysis, fermentation, ethanol purification

one of the main conclusions of a study looking at well-established oil and wet corn-based refining industries [4]. The same study concludes that biofuels will be the main end product of companies investing in the biorefinery.

Several technologies are currently under development to produce biofuels from lignocellulosic biomass. Some references list available technologies and their current development stage based on publicly available information [5, 6]. It can be concluded that none of these technologies is yet operating at a commercial scale. One of the reasons is that they are not competitive with current bioethanol production processes that use corn and sugar cane as raw material. However, targeted process efficiencies should render these processes competitive in the near future. This is shown in many published process assessments that use targeted efficiencies instead of current conditions for both the biorefinery and pulp and paper industry: enzymes are assumed to be available at a very low cost in biochemical process assessments [7], separation processes are assumed to be well established [8], and pulp and paper mills are considered to be modern [9].

Thorp et al. [10, 11] divided the production routes for biofuels into two groups based on their operating principles:

- **Thermochemical biorefinery processes:** raw material is thermally degraded into carbon oxides and hydrogen, which are then synthesized into the targeted end product, and;
- **Sugar platform biorefinery processes:** polysaccharides are first converted into sugars, which are then further fermented to produce the targeted end product.

One of the promising sugar platform routes to produce biofuels has been termed Value Prior to Pulping (VPP), where hemicelluloses are extracted from wood chips before pulping for ethanol and chemical production. The cellulose continues to be used for pulp and paper production [8, 12, 13]. The first demonstration scale bioethanol IFBRs are currently under construction in the U.S., and one of those is the integration of the VPP process into a kraft pulp mill in Old Town, Maine.

A promising thermochemical process concept is black liquor gasification, where the dissolved organics from the pulping process are converted into synthesis gas and further to energy, fuels, or chemicals. The most comprehensive study on this process was done by Larson et al. [9].

Few systematic comparisons of IFBR raw material and process options for biofuel production have been published to date. Biorefinery techno-economic studies have generally considered one process at a time, and because the assumptions are not the same in each study, comparisons are difficult. U.S. DOE-funded research reports are one exception. They use same general approach and basis for techno-economic assessments; however, they have been done for stand-alone facilities [7, 14, 15].

Selecting the most profitable or most suitable process or process combination to be integrated into a pulp and paper mill from the many possible options (raw material-technology combinations) is a complex task. One method proposed for the selection of a biorefinery process uses a superstructure of biorefinery options, PSE tools, and optimization [16], which targets process selection based on generic design methodologies. Another method, used in a pulp and paper mill retrofit case study [17], is called Large Block Analysis (LBA), and holds significant promise. However, this method has not yet been applied in the biorefinery context.

The economies of scale for biorefining have been addressed in certain cases [18-20]: the bigger the production capacity is, the lower the production costs and capital investment costs are on a per tonne of product basis. However, a small IFBR might be economically viable when it is integrated into a pulp mill. This aspect is very important in strategic decision making, especially for the production of bulk products such as bioethanol.

There is an important need for evaluating different technologies on as similar a basis as possible using a systematic methodology, even given the risks implicated due to different design bases from different sources of information.

OBJECTIVE

This paper focuses on the integration of bioethanol production processes into a pulp and paper mill. The objective is to compare the techno-economics of different bioethanol IFBR design options in order to be able to screen out non-profitable options. This approach takes into account the impacts of IFBR integration (integration into the pulp and paper mill and integration of several bio-processes). A North American hardwood kraft pulp mill is the case study context.

METHODOLOGY

A conventional techno-economic assessment is used in order to calculate the profitability of IFBR for the case study. First the raw material inventory and assessment for the mill location was completed. Then existing and emerging technologies for bioethanol production were examined to define IFBR cases. Different mill configurations (current scenario and modernized mill scenario) were examined to account for different integration possibilities if mill were to be modernized concurrently with biorefinery implementation. Mass and energy balances and production and capital investment costs were calculated based on reference information for both scenarios. Last, the profitability of each case was estimated by calculating the after-tax Internal Rate of Return (IRR).

TABLE IV. Reference descriptions of biorefinery processes.

Technology	Description of available information
High temperature gasification [9]	Forest biomass gasification; mixed alcohol production balances of reference are not used in this study
Medium temperature gasification [15]	Detailed balances and cost definitions for medium temperature gasification of forest biomass
Mixed alcohol synthesis and ethanol separation [15]	Detailed balances and cost definitions for MA synthesis and alcohol separation processes
Syngas fermentation [25, 26, 28]	Only estimates of production costs available, no mass and energy analysis available
Acidic hydrolysis [29]	Mixed hardwood to ethanol process balances and cost analysis
Enzymatic hydrolysis [7, 14, 30]	Detailed balances and costing for corn stover-ethanol process
Corn ethanol [14, 31, 32]	Detailed balances and costs for dry milling corn ethanol plant
Hemicellulose extraction [8, 13]	Balances and costs of extraction of VPP options

TABLE V. IFBR cases considered (raw material-process combinations, see Tables II and III for processes).

	T1	T2	T3	T4	S1	S2
Biomass	✓	✓	✓	✓	✓	✓
Pulp wood	✓	✓	✓	✓	✓	✓
Hemicelluloses					✓	✓
Lignin	✓	✓	✓	✓		
Corn						✓
Corn stover	✓	✓	✓	✓	✓	✓
Food processing waste						✓

The calculations were done using Microsoft Excel. The methodology and assumptions are described in the following sections.

Raw material assessment

The availability of raw material in the region around the mill was defined for raw materials (Table I).

Raw material costs at the mill gate as a function of plant capacity were defined using a published method [21] and mill region-specific information [2]. The raw material yield was assumed to be constant in the area where the mill is located, and was based on availability in a 50-mile radius. The hemicelluloses of pulpwood processed at the mill (10% of pulpwood) and lignin (35% of pulpwood) are assumed to be available at energy price (coal price), larger amounts are available at pulpwood price. Agro-based raw material base costs were taken from the literature [3, 22], and forest-based raw material base costs are calculated using actual prices.

Technology assessment

The processes to produce ethanol were divided based on the definition given by Thorp et al. [10, 11]. In the following sections, the generic routes to produce ethanol and the IFBR design cases (raw material – route combinations) are defined.

Thermochemical processes

Thermochemical conversion routes are suitable for all raw material types. However, generally sugar-containing and starchy raw materials are more easily converted to ethanol through sugar platform processes.

Bioethanol production through thermochemical routes is not yet considered to be commercial. However, parts of the process employ well-known technologies. Thermochemical bioethanol production consists of four main steps, 1) feedstock preparation and drying, 2) thermal degradation of biomass into synthesis gas (syngas), 3) gas cleaning by removing inorganic components and adjusting the H_2:CO molar ratio via the water-gas shift reaction, and 4) gas compression and synthesis either with biological catalysts (enzymes) to ethanol or with chemical catalysts to mixed alcohols (MA).

Feedstock handling and drying before gasification, and product gas cleaning and conditioning are well developed process steps. Thermal degradation can be done with several gasification technologies. The two proven technology groups are high temperature (~1000°C) and medium temperature (~600°C) gasification. In high temperature gasification, part of the feedstock is combusted in the gasifier with addition of oxygen to generate the required heat for the endothermic gasification reactions. Lower temperatures are sufficient in indirectly heated gasifiers (steam reformers); they typically use external combustion of product gas or char to provide the energy for the process. The heat is transferred to the feedstock by indirect heating and solid "sand" circulation [15, 23].

The main processing step, alcohol synthesis, has not reached the commercial stage. However, there are several studies considering alcohol synthesis with chemical and biochemical catalysts [26, 28]. In chemical synthesis, the end product is a mixture of alcohols – methanol, ethanol and higher-molecular weight alcohols – from which the targeted component(s) can be separated. In biosynthesis, syngas is fermented to ethanol. The advantage of biosynthesis over chemical synthesis is that the syngas can be converted largely to ethanol instead of several alcohols, and therefore the ethanol yield is higher. On the other hand, biosynthesis is constrained because of poor solubility of CO in ethanol. Therefore, converting syngas to ethanol can take up to 25 days in contrast to 1-2 days with MA (mixed alcohol) synthesis. Also, by adjusting the H_2:CO molar ratio, MA synthesis can be optimized to achieve a higher ethanol yield. [9, 15, 24-26]

By combining these different process steps to produce ethanol, four thermochemical routes were established (Table II).

Sugar platform processes

The sugar platform is suited for most types of raw materials. However, it is not yet possible to convert lignin and some other components of the feedstock such as proteins and fats into sugars, and subsequently to ethanol with biochemical processes. Sugar platform ethanol processes can be divided into four main processing steps: 1) during pre-treatment, the feedstock is fractionated mechanically, thermally, and/or chemically, 2) during saccharification, polysaccharides are converted to sugars, 3) during fermentation, the sugar(s) are converted to ethanol and 4) during

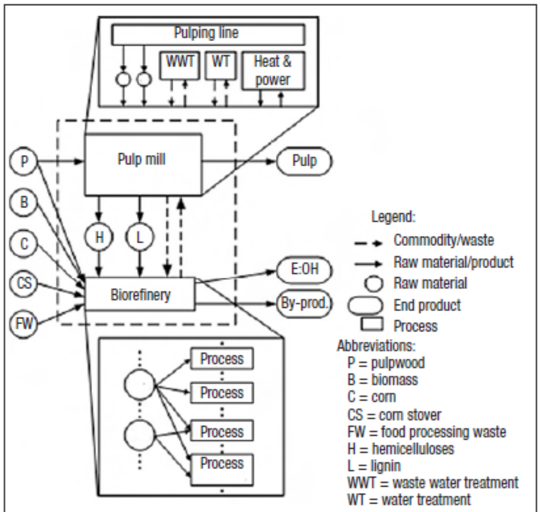

FIG. 1. Case mill IFBR context.

purification, ethanol is separated from the fermentation broth.

Typically, technologies are characterized based on their saccharification process step: acid or enzymatic hydrolysis. The acid hydrolysis route uses either dilute or concentrated acid (mainly sulphuric acid) to break cellulose and hemicellulose into sugars. In the enzymatic hydrolysis route, the conversion is done with a mixture of cellulase enzymes. Enzymes are capable of breaking down polysaccharides to sugars, whereas acids will further degrade sugars to smaller molecules. Although enzymatic hydrolysis is thus selective, it is generally slower than acid hydrolysis. The second critical difference between hydrolysis processes resides in the preparation for fermentation. Because of the pH requirements for fermentation, the acid hydrolysis route needs neutralization and/or acid recycling before the fermentation step. The enzymatic hydrolysis route works in the same pH range as fermentation and thus does not need significant pH adjustments.

Another dimension to the sugar platform processes is the pre-treatment step. Perhaps the most comprehensive comparison between pre-treatment processes was conducted by CAFI (Consortium for Applied Fundamentals and Innovation). They compared five pre-treatment technologies for corn stover based on individual projects that characterized and optimized the technologies [27]. The biomass pre-treatment considered for each option was that considered in the referenced studies.

Some sugar platform processes also produce ethanol as co-product. An example is acetone-butanol-ethanol (ABE) process. These processes are not considered in this study.

Based on the above considerations, two generic routes for the sugar platform were defined for this study (Table III).

Case study design basis

Several technology providers exist for the process routes described above, each of them having different process configurations and therefore also different economic performance. However, technology-specific mass and energy balance information for systematic and reliable comparison is not publicly available.

TABLE VI. Economic assessment variables.

Tax	30% (when income positive)
Depreciation	MACRS (Modified Accelerated Cost Recovery System) with 200% declining balance depreciation method and 7-year recovery period
Investment	100% paid in 2011
Working capital	5%
Plant life	20 years
Inflation factor	3%
Start up	2012 (75% production), 2013 — 2032 (100% production)
Selling price of ethanol	2$/gal
Selling price of mixed alcohols (other than ethanol)	1.15$/gal
Price of Distillers Dry Grind with Soluble (DDGS) (a by-product of the corn ethanol process)	100$/bdt

Therefore, mainly governmentally funded, published research reports that include comparable mass and energy balances have been used to describe these technologies (Table IV). Furthermore, the references are assumed to represent the routes for all possible raw materials, even though the reports consider specific processes/technologies for specific raw materials. Also, references are assumed to be valid for a range of plant capacities.

Case definitions

The raw material-process combinations considered in this study are shown in Table V. These combinations describe the processing of one type of raw material (Table I) with one of the identified process routes (Tables II and III). These IFBR cases can be further combined to form hybrid IFBR cases (several raw materials-one process route).

Ethanol yields for different processing routes were taken from references (Table IV):

- Thermochemical route alcohol yield is 90% of the theoretical maximum yield [15]
- 85% of the mixed alcohols yield is ethanol [15]
- Woody raw materials (B, P, L) have the same yields in thermochemical cases, but corn stover (CS) has lower yield due to its ash content (10% ash assumed)
- Ethanol yields are 65% and 75% of theoretical maximum for the acid and enzymatic hydrolysis cases [7, 14, 29]
- The ethanol yield from food processing waste is assumed to be 50% of corn ethanol yield.

Scenario definition

Mill scenarios

The case study mill IFBR is summarized in Fig 1.

All cases were integrated into the host kraft pulping process keeping pulp production unchanged, except for the case of pulp wood-to-ethanol, where no pulp is produced. The biorefinery processes use existing steam and power generation, water treatment, and waste water treatment systems until their excess capacity is fully utilized.

The case study mill wished to consider mill modernization.

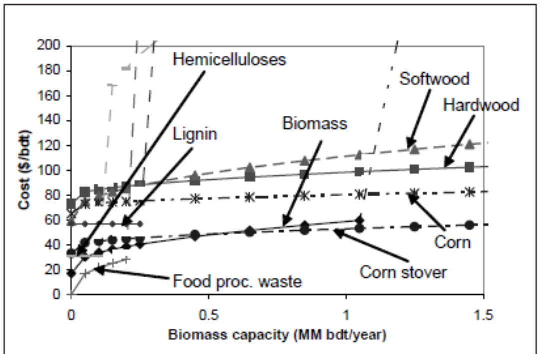

FIG. 2. Raw material supply curves.

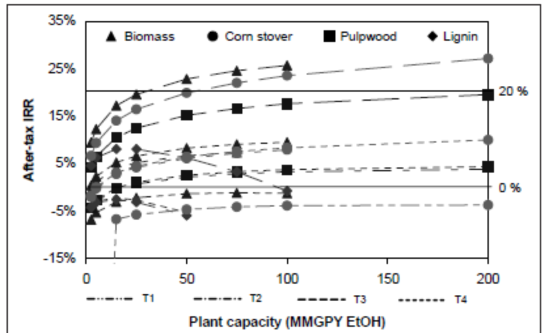

FIG. 3. After-tax IRR of single line thermochemical cases as function of plant capacity

The current and modernized mill configurations were considered to account for the different interfaces with the biorefinery processes. The main objectives of the mill modernization were production capacity increase, energy and chemical recovery system updates, and water cleaning system capacity increase. The main changes with the modernized mill were the increase in hemicellulose and lignin availability for the IFBR, and the boiler update enabled the burning of solid residues from the biochemical cases.

Both mill scenarios were assumed to start at the same point in time, hence, mill modernization and biorefinery implementation would be concurrent. Since the starting point is fixed, the impact of time on economic variables such as prices, on raw material availability and on technology development was the same for both scenarios.

Economic scenarios

Several economic parameters must be defined in order to have comparable results. The economic assumptions used in the literature (Table IV) were applied in this study, e.g. the departmental capacity scaling factors, indirect investment costs, and contingencies. In Table VI the variables for after-tax Internal Rate of Return calculation are given.

Mass and energy balances & cost calculation

Mass and energy balances

Based on the literature (Table IV) and the mill scenarios, mass and energy balances were calculated. This defines the possible level of integration. As integration aspects, energy (heat and electricity), purified water, and waste water were considered. The demand of these aspects defined whether the case mill capacity was sufficient to provide these demands, or at which ethanol plant capacity new systems are needed.

Capital investment costs

The capital investment cost should be calculated at the departmental level in order to account for cost decreases due to the integration. This information can be found in the literature, and therefore this level of detail was used. The equation for total investment costs (TIC) is:

$$TIC = \Sigma_i \left[\left(\frac{M}{M_{ref}} \right)^{ai} C_{eq,i} \right] \quad (1)$$

where i represents the departments of the biorefinery plant including integrated departments, M represents the production capacity of the plant and M_{ref} the production capacity of reference plant, a_i is the scaling factor for department i, $C_{eq,i}$ is the installed equipment cost of department i in the installation year.

The three integration departments (energy, purified water and waste water systems) are subtracted if the mill's existing capacities were sufficient for both the pulp mill and biorefinery. In addition to this integration aspect, in hybrid biorefinery cases the departments that can be combined (such as distillation or fermentation in the sugar platform cases) were calculated by scaling the department of one of the single production lines to total capacity of the combined case. This way full integration benefits would be exploited.

From TIC the total project investment (TPI) is then:

$$TPI = TIC * (1 + ind + cont) \quad (2)$$

Here *ind* is the indirect project costs (engineering, field expenses, etc.) and *cont* the contingency costs as percentage of total installed equipment cost.

Manufacturing costs

Bioethanol manufacturing costs with capacity M, C_M, consist of variable costs (raw material, chemicals and utilities) and fixed costs (insurance, maintenance supplies):

$$C_M = \Sigma_j p_j m_j + ins * TPI + maint * TIC \quad (3)$$

where j represents streams of the process, p_j is the unit price of stream j, m_j is the mass flow of stream j, *TIC* is total installed equipment costs, *TPI* is total project investment cost, *ins* and *maint* are insurance and maintenance supplies costs as a percentage of *TPI* and *TIC*. It was assumed that there are no additional labour costs for the biorefinery, i.e. operators and other personnel at the pulp mill would also be qualified to manage and control the new biorefinery process.

Profitability estimation

After-tax Internal Rate of Return (IRR) was used to measure the profitability of each scenario. IRR is calculated from net profit and the TPI (equation 2) assuming the economic variables given in Table VI. IRR was calculated according to the following:

$$NPV = \sum_{t=0}^{20} \frac{income_t}{(1+IRR)^t} = 0 \quad (4)$$

where *NPV* is the net present value, and t is the plant life used in this study. The *income* is annual after-tax:

$$income_t = \lfloor (I_{EtOH} + I_{by\text{-}prod} - C_m)(1+\inf)^t - depr_t \rfloor (1 - tax) \qquad (5)$$

where I_{EtOH} is the income from ethanol, $I_{by\text{-}prod}$ the income from by-products (such as mixed alcohols, DDGS, or excess electricity), C_M is the manufacturing cost (these three variables are zero in the year t=0, which is the construction year), *inf* is the inflation factor, *depr* is the depreciation of the plant based on the depreciation system, and *tax* is the national income tax (applied only when income is positive).

RESULTS AND DISCUSSION

In Fig. 2 the raw material assessment results and supply curves of raw materials are summarized.

The unit price of raw material at the mill gate decreased as a function of hauling distance, which has also been found in other studies [20, 21]. When some critical capacity is reached, for example the amount of hemicelluloses at the mill, then the cost curve increases suddenly. Energy wood and corn stover raw materials have the lowest unit price except at small biomass capacities where hemicellulose and food processing waste have a lower cost. Pulpwood has the highest unit price[1]. The profitability of the single line IFBR cases are shown in Figures 3 and 4, and profitability of each case with 25 and 75 MMGPY ethanol production capacities are summarized in Table VII.

TABLE VII. After-tax IRR of single line cases with 25 and 75 MMGPY ethanol production capacities

Process option	Feedstock	25 MMGPY	75 MMGPY
High temp. gasification + mixed alcohol synthesis (T1)	Biomass	−2 %	−1 %
	Pulpwood	–	–
	Lignin	–	–
	Corn stover	−6 %	−4 %
High temp. gasification + syngas fermentation (T2)	Biomass	5 %	7 %
	Pulpwood	1 %	3 %
	Lignin	−3 %	–
	Corn stover	4 %	7 %
Steam reforming + mixed alcohol synthesis (T3)	Biomass	20 %	25 %
	Pulpwood	12 %	17 %
	Lignin	8 %	3 %
	Corn stover	16 %	22 %
Steam reforming + syngas fermentation (T4)	Biomass	7 %	9 %
	Pulpwood	1 %	3 %
	Lignin	−3 %	–
	Corn stover	5 %	8 %
Acid hydrolysis + fermentation (S1)	Biomass	5 %	–
	Pulpwood	11 %	15 %
	Hemicelluloses	–	–
	Corn stover	22 %	30 %
Pre-treatment + Enzymatic hydrolysis + fermentation (S2)	Biomass	−3 %	–
	Pulpwood	–	–
	Hemicelluloses	–	–
	Corn stover	8 %	13 %
	Corn	26 %	37 %
	Food proc. waste	–	–

The steam reforming options (T3 and T4) have higher IRR than the high temperature gasification cases (T1 and T2), which have higher investment costs and therefore lower IRR values. The mixed alcohol synthesis option (T3) has better economics than the syngas fermentation options (T4). This is due to higher investment costs for the fermentation route. In high temperature gasification cases syngas fermentation (T2) and mixed alcohol synthesis (T1) are comparable. Low cost raw materials, such as biomass and corn stover, are most profitable when comparing raw material options for each processing route.

Of the sugar platform cases, the corn ethanol process was found to have the highest IRR. The food processing waste case is comparable, but only at small capacity. The corn stover and pulpwood cases have the second highest IRR values, primarily because these processes have lower yields compared to the corn ethanol case. All other cases have lower IRRs and are not shown in the figure. The acid hydrolysis process had higher IRR value than the enzymatic hydrolysis process with all raw material options.

Validation of these results is difficult. However, it can be said that differences in prices, especially in chemical prices, result in lower profitability values in this study compared to the case studies published in the literature [7, 8, 33].

The results of single line cases with two ethanol production capacities, 25 and 75 MMGPY are presented in Table VII.

Some examples of thermochemical hybrid cases are shown in Figure 5, and sugar platform hybrid cases in Figure 6. All shown cases are combinations of two raw materials using the same processing route.

Only the results for one raw material share proportion, 1:1, are shown in the thermochemical hybrid figure (Fig. 5). As can be estimated from the single line cases (Fig. 3), the hybrid case will have a high IRR value, if the single-line cases have high IRR values. For example steam reforming and mixed alcohol synthesis of biomass and corn stover has high IRR value. However, combinations of low single-line IRR values might have higher IRR values when combined, because of the lower capital investment costs (syngas cleaning and alcohol synthesis steps of the two cases could possibly be done with the same equipment).

Similar results were found for the sugar platform hybrid cases (Figure 6). Combining corn with other raw materials increases substantially the profitability of the other raw material. However, the total profitability will be lower than for the corn feedstock (only) case. For example, corn (95% of ethanol process feedstock) and hemicelluloses as hybrid case feedstock would have very high IRR value, although only the ethanol purification process could be integrated for these raw materials.

It was found that the modernized mill scenario impacted only the sugar platform cases. The impact of mill modernization can be seen by comparing Figures 4 and

[1]Specific case study data for biomass feeds at the time of the study were used, at which point the price of corn was unusually low

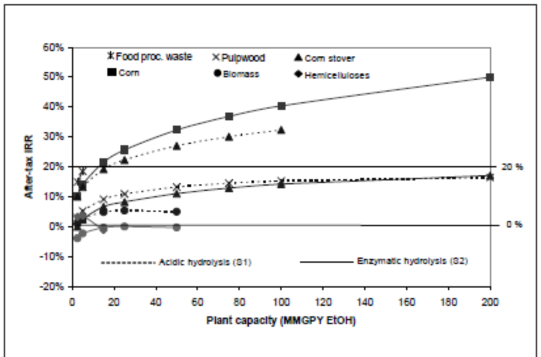

FIG. 4. After-tax IRR of single line sugar platform cases as function of plant capacity.

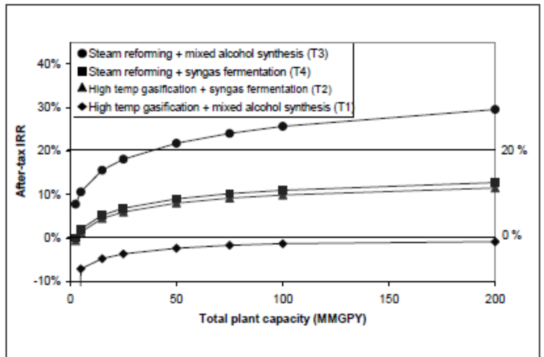

FIG. 5. After-tax IRR of hybrid thermochemical cases (biomass (50%) + corn stover (50%)) as function of plant capacity.

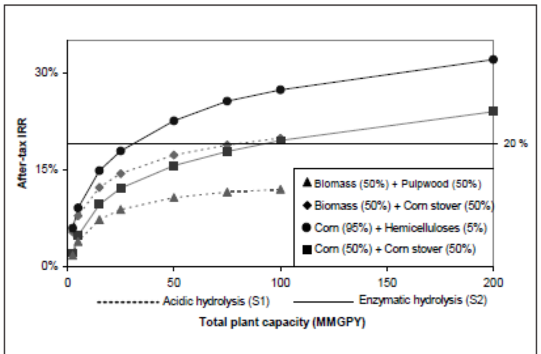

FIG. 6. After-tax IRR of combined sugar platform cases as function of plant capacity.

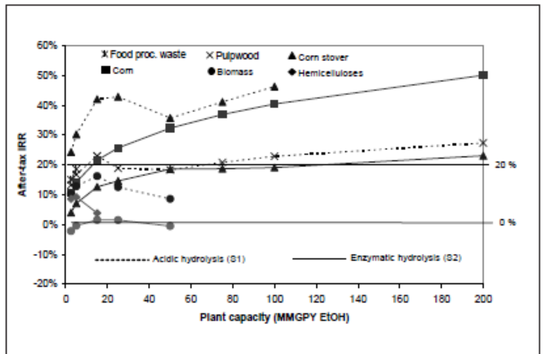

FIG. 7. Modernized mill scenario, sugar platform after-tax IRR.

7. Surprising differences were observed for the corn stover case: after modernization, it has an even higher IRR value than the corn ethanol case for small capacities. Also, all other cases except the corn to ethanol case have a ~10% higher IRR. This is mainly due to the capacity of the modernized mill to handle the solid residue from the sugar processes in the modernized energy and chemical recovery systems. The results of this scenario are comparable to published results for hemicellulose- and pulpwood-based ethanol [8, 33].

Screening out non-profitable options based on the methodology employed appears to be feasible. However, without knowing the sensitivity of the IRR values on the made assumptions, a large set of potentially acceptable options has to be kept in order to, for example, account for possible future price changes. No ranking of the considered options was therefore reported.

CONCLUSIONS

An order-of-magnitude techno-economic assessment was completed for a wide range of biorefinery technologies suitable for the production of ethanol, considering the specific conditions for a case study pulp and paper mill. Of the single-line thermochemical ethanol production cases, only corn stover and pulpwood based production were found to be profitable at a large scale due to raw material availability and prices. However, biomass-based thermochemical ethanol (MA synthesis) seems to be profitable for smaller capacities.

For the set of assumptions in this particular analysis, single-line sugar-platform forest-based routes were less economically attractive when compared to thermochemical-based processes, without combining them with corn ethanol production. For instance, the hemicellulose extraction case integrated into a corn ethanol plant (5% of ethanol from hemicelluloses) is economically interesting. Especially if there is a need to expand pulp production, this option could be considered as a way to keep the organic load of a recovery boiler constant.

Modernizing the mill only has a positive impact on the sugar platform cases, because modernized boilers would be designed to be capable of burning the solid residues of the bioethanol production process. It increases the IRR of all cases until the capacity of the boilers has been reached.

In general, the techno-economic approach used in this study can be used to compare the order-of-magnitude profitability of different biorefinery cases. The results of this study are based on published estimates of biorefinery mass and energy balances, as well as capital and operating costs. This approach incorporates uncertainty, because inconsistent design and techno-economic analysis methods have been used in different published studies. For example, in the case of high temperature gasification [9] the investment cost estimates are made by an engineering consulting company, whereas in the low temperature gasification case [15] the research group estimated installed equipment costs by combining literature, vendor quotes, and software calculations. Inadequate data are available to validate how realistic or comparable the cost estimates are in each case. Process and price assumptions (raw material yield/area, ethanol yield/raw material/route, etc.) should be validated on a case-by-case basis to obtain comparable results. Finally, technical uncertainties should be considered as well as possible subsidy scenarios using sensitivity analysis techniques.

In conclusion, several parameters were found to have a significant impact on the economic viability of sugar platform ethanol production which may increase its attractiveness compared to thermochemical ethanol production in an IFBR.

ACKNOWLEDGEMENTS

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Résumé: Les technologies de plateforme de traitement thermochimique et de traitement des sucres permettent de transformer les matières premières lignocellulosiques en éthanol. Le taux de rendement interne après impôts peut servir à déterminer la faisabilité économique de ces technologies. Une usine de pâte kraft a évalué plusieurs concepts d'installations de bioraffinage forestier avant de prendre une décision. Si l'on se base sur les prix de l'usine et la disponibilité des matières premières, ainsi que sur les données publiées sur le bioraffinage, il est clair que l'éthanol produit à partir du maïs est la meilleure option possible, suivie de la synthèse thermomécanique des alcools mixtes.

Reference: HYTÖNEN, E., STUART, P.R. Integrating Bioethanol Production into a Kraft Pulp Mill - Technology Assessment. *Pulp & Paper Canada* 110(5): T58-T65 (May/June 2009). Paper presented at the 95th Annual Meeting in Montreal, Que., February 3-4, 2009. Not to be reproduced without permission of PAPTAC. Manuscript received September 1, 2008. Revised manuscript approved for publication by the Review Panel March, 2009.

Keywords: INTEGRATED FOREST BIOREFINERY, INTEGRATED KRAFT PULP AND PAPER MILL, LIGNOCELLULOSIC, THERMOCHEMICAL, SUGAR PLATFORM, ETHANOL, MIXED ALCOHOL SYNTHESIS, INTERNAL RATE OF RETURN

APPENDIX B – Article: Biofuel production in an integrated forest biorefinery – technology identification under uncertainty

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Biofuel Production in an Integrated Forest Biorefinery—Technology Identification Under Uncertainty

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Lignocellulosic biorefinery processes for biofuel production are developing rapidly but their commercialization may still take some years. Incorrectly identifying the most promising technologies from the existing options based on their current development stage, estimated future costs of plant construction, prices of raw materials and end products poses a risk of making less favourable decisions. To mitigate these risks in design decision making, technical- and market-based uncertainties should be considered in techno-economic assessments. Monte Carlo analysis can be used in a systematic technology identification approach to account for these risks in preliminary screening of integrated forest biorefinery options. This paper will discuss the large block analysis approach including uncertainty estimations with Monte Carlo simulation. The results of using this approach in a case study to investigate the feasibility of integrated biofuel production from several raw materials with several technologies at a North American integrated kraft pulp and paper mill are also discussed. These results will help this mill to select the right technology, or combination of technologies, for further consideration in the context of biofuel production.

Keywords: Integrated Forest Biorefinery (IFBR), Pulp and Paper Industry (P&P), Production Economics, Monte Carlo Analysis, Lignocellulosic Biofuels.

RESEARCH ARTICLE

1. INTRODUCTION

1.1. Background

More and more forestry companies are pursuing new revenue streams from the emerging lignocellulosic biorefinery industry by producing biofuels as main products. The multitude of process and product options, combined with the existing and developing raw material base in the mill region, makes process design decision making a difficult task. Moreover, the current financial and economic situation and uncertain future combined with the very capital intensive nature of the new business complicate the task even further.

Using a common basis and method for comparing the possible process designs systematically can help decision making. The basis can be established by combining public domain process design studies that provide simulation- and modelling-based mass and energy balances and capital investment estimates with theoretical estimates of product yields from various feedstocks. Using one common well-developed assessment method consisting of traditional techno-economic analysis, scale-up rules, and one common price/cost basis instead of several prices used in the published studies, will generate comparable information of entirely different design scenarios.

1.2. Literature Review

Evaluating an emerging and unknown industry necessitates addressing uncertainties. In process design, four main sources of uncertainty were identified by Pistikopoulos[1]—model inherent, process inherent, external and discrete. In the early stages of biorefinery process design, models are certainly very simple and often linear; on the other hand many of the biorefinery processes are still at the laboratory development stage and their future development level can only be estimated. Therefore, it is very difficult to address the first two sources of uncertainty separately. Moreover, external uncertainties, e.g., in feedstock and product prices, have an impact which might be more severe than those of a technical nature.

Stochastic risk analysis provides one way of incorporating the uncertainties into process design. Instead of defining fixed scenarios like in scenario planning or considering one model variable at a time in sensitivity analysis, stochastic risk analysis combines the strengths of both approaches: after the most important step of risk analysis,

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the definition of risk variables,[2] their values are described using a probability distribution function. When many combinations (often 10^5–10^7) of the risk variable values are used, many different scenarios are considered. These combinations include not only the most probable but also the best and worst case scenarios.

Perhaps the best known stochastic risk analysis method is Monte Carlo Analysis (MC). It uses a "brute force" method on sampling the risk variable values randomly from the probability distributions. Faster and mathematically more complex sampling methods have been developed, e.g., Latin Hypercube Sampling or Hammersley sequence sampling. They are also shown to give better distributed random numbers and more efficient stochastic analysis.[3]

MC has also been used in biorefinery process design case studies. Aden et al. use it to incorporate external uncertainties to the detailed design assessment of a lignocellulosic ethanol production process[4] and similarly, Richardson et al. in the case of corn ethanol plant economic performance.[5] However, they only considered end product prices as risk variables. In forest industry applications, MC has been used for example by Janssen et al. for screening out deinked pulping retrofit design scenarios for an integrated newsprint mill[6] and Ince and Buongiorno used MC to select new technology for a hypothetical greenfield paperboard mill.[7]

Stochastic risk analysis can result in a better understanding of the uncertainty of decision making criteria and the impact of external uncertainties on the profitability of different design scenarios. Using relatively simple models and easy implementation (compared with more complex sampling methods) favour the use of the Monte Carlo method even though it is normally considered to be a computationally heavy risk analysis method.

1.3. Objective of the Study

This paper focuses on applying risk analysis in a techno-economic assessment comparing several biofuel production scenarios at a North-American integrated hardwood kraft pulp and paper mill. The first objective is to demonstrate how the selection of process design options can be enhanced by using stochastic risk analysis. The second objective is to build a common calculation basis for comparing different technologies and for comparing biochemical and thermochemical biofuel production scenarios. The first part of the case study results was published earlier by the same authors.[8]

1.4. Methodology

In this study, large-block analysis (LBA) was used: processes and their mass and energy balances are considered as large blocks (input–output-model) in conventional techno-economic analysis and Monte Carlo risk analysis.

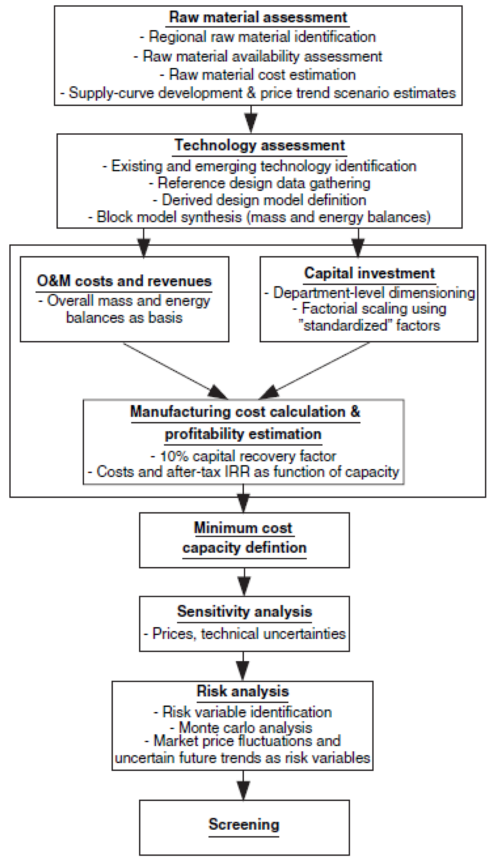

Fig. 1. Techno-economic analysis method block diagram.

The LBA method (see Fig. 1) consists of the following the steps:

- Identification of raw materials and definition of raw material prices in the case mill region based on public databases and using published methods[9]
- Assessment of the process design options, both existing and emerging, to produce biofuels from available feedstocks: identification of technologies and development of basic mass and energy balance models. The emerging and therefore unknown processes were designed starting from well-defined processes: ethanol production with biochemical and thermochemical processes from corn stover and woody biomass, and Fischer-Tropsch liquids (FTL) production from woody biomass.[10–13]
- Estimation of capital investment costs, production costs, revenues and profitability as a function of plant capacity. To have comparable results, the same basis for factorial economic evaluation of all design options was used.

- Definition of production capacities with low production costs
- Sensitivity analysis of IRR by varying economic variables
- Risk analysis:
  - Identification of the risk variables: identification of uncertain economic variables having a major impact on IRR with sensitivity analysis and analysis of the historical data
  - Construction of probability distributions for the identified risk variables
  - Calculation of the IRR and its probability distribution using the defined distributions and public trend forecasts for energy prices. The Monte Carlo method was used.
- Screening out non-promising design options using profitability as screening criteria

The main assumptions used in the economic analysis are listed in Table I: different exponent, factors for the capacity-factored investment cost estimation method for scaling reference capacity to considered design capacities in this study; indirect capital investment costs; fixed operating and maintenance (O&M) costs; construction schedule; and project start-up schedule. Prices of feedstocks and end products are presented in Table II.

Table I. Calculation assumptions.

Plant capacity scaling factors (exponent)	Biochemical[10,11]
	Saccharification – 0.7
	Fermentation – 0.95
	Distillation – 0.71
	Others – 0.6
	Thermochemical[12]
	Feed handling – 0.75
	Gasification & O_2 plant – 0.65
	Synthesis – 0.72
	Alcohol separation – 0.8
	Others – 0.6
Indirect costs	Thermochemical scenarios 39% of total investment cost (TIC)[12]
	Biochemical scenarios 64%[4]
Fixed costs	Maintenance supplies 2% of TIC, insurance and local taxes 2% of total project investment (TPI), no labour (existing mill personnel assumed to be able to run the biorefinery process)
Contingency	5% of TIC
Working capital	5% of TPI
Project	2 year construction, starting 2010
	20 years lifetime
	100% project financing in the first year of construction
Start-up	1st year of production – production 50% of nameplate capacity, 75% of O&M costs
	2nd year of production – production 75% of nameplate capacity, 100% of O&M costs
	3rd year of production – full capacity
Incentives and subsidies	No product subsidies
	No investment incentives

Table II. Base case price information.

Products	Ethanol – Energy content corrected gasoline price ($HHV_{ethanol} = 29.7$ MJ/kg, $HHV_{gasoline} = 47.34$ MJ/kg)
	Mixed alcohols (MA) – Energy content corrected gasoline price ($HHV_{MA} = 31$ MJ/kg, $HHV_{gasoline} = 47.34$ MJ/kg)
	Fischer-Tropsch liquids (FTL) – Diesel retail price
	By-products – Distillers dry grind with solubles (DDGS) 0.1\$/kg, furfural 0.33\$/kg, acetic acid 1.17\$/kg
	Transportation costs of 1 ¢/kg subtracted from the retail prices of fuels[13]
Energy	Electricity – 6.1 ¢/kWh, low pressure steam – 1.7 ¢/kg,
Fuels	Coal – 40\$/t, natural gas – 5.6\$/MJ,
Chemicals	H_2SO_4 – 120\$/t, NaOH – 650\$/t, Lime – 100\$/t, oxygen – 63\$/t
Enzymes	0.033\$/kg ethanol (corresponds to 0.1\$/gal ethanol)
Feedstock	Capacity dependent prices presented by Hytönen and Stuart[8]

1.5. Biofuel Production Scenarios at the Case P&P Mill

The pulp and paper (P&P) mill and biorefinery context of this case study is described in more detail by Hytönen and Stuart,[8] including the raw material assessment, technology descriptions and preliminary profitability estimates for bioethanol process design options. In addition to the scenarios described there for bioethanol production, biofuel production scenarios in this study also include thermochemical mixed alcohols and FTL production using agricultural and forest based feedstocks.

Table III. Possible product-process combinations in an integrated fuel-producing forest biorefinery.

	Product	Process
1	Ethanol + higher alcohols	Gasification, MA synthesis, ethanol separation
2	Ethanol	Gasification, synthesis gas (syngas) fermentation, ethanol purification
3	Ethanol + higher alcohols	Steam reforming, MA synthesis, ethanol separation
4	Ethanol	Steam reforming, syngas fermentation, ethanol purification
5	Mixed alcohols	Gasification, MA synthesis
6	Mixed alcohols	Steam reforming, MA synthesis
7	FTL	Gasification, FTL synthesis
8	FTL	Steam reforming, FTL synthesis
9	Ethanol	Acid hydrolysis, fermentation, ethanol purification
10	Ethanol	Pre-treatment, enzymatic hydrolysis, fermentation, ethanol purification
11	Ethanol	Acidic pre-hydrolysis, simultaneous saccharification and fermentation (SSF), ethanol purification
12	Ethanol + acetic acid	Near-neutral green liquor extraction, acidic hydrolysis, fermentation, ethanol purification

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The possible process designs with the main products are listed in Table III; these designs can be applied to different feedstock options leading to 42 possible design scenarios.

2. RESULTS AND DISCUSSION

2.1. Production Capacity Definition

As was discussed in the raw material cost assessment by Hytönen and Stuart,[8] the feedstock availability sets a limit to maximum plant capacity. This and the yield difference between different scenarios is the reason for having varying maximal production capacity and different cost of production as shown in Figure 2. Table IV lists all design scenarios with the main design parameters: feedstock, production capacity, fuel yield from the feedstock, capital intensity of the design, operation and maintenance costs, by-product credits and the main references. Values in the table are defined at the lowest production cost- and/or highest possible production rate capacity; however, no optimisation was used in achieving these capacities.

As shown in Figure 2, the economies of scale for biorefinery processes when they are integrated into the case mill do not seem to be similar to generic stand-alone lignocellulosic ethanol production scenarios considered for example by Wright and Brown.[14] They show that biochemical lignocellulosic ethanol production for example has lowest production cost at capacities of more than 150 million gallons per year (MMGPY) gasoline equivalent (GEq) (corresponds to 570 ML/year), or gasification and FTL-synthesis at capacities larger than 400 MMGPY GEq (1500 ML/year), whereas our results show that the low cost capacities (constrained in some scenarios by raw material availability) are much lower in this case study, below 250 ML/year GEq for all considered scenarios. This leads to relatively small production capacities that have highest economic potential for the mill under study.

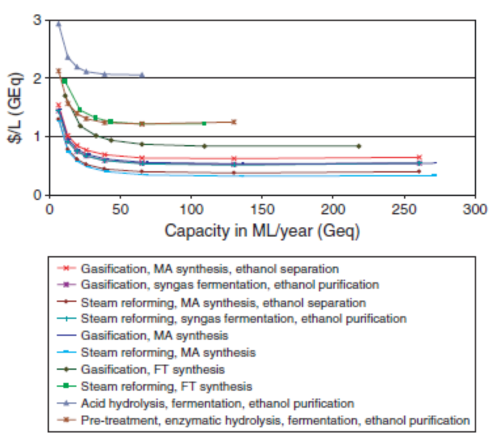

Fig. 2. Production cost of main product as a function of production capacity (in million litres annually), woody biomass as feedstock. 10%/yr capital recovery factor assumed.

One of the observations is that different scenarios have different promising production capacities ranging from 19 ML/year ethanol (5 MMGPY) up to 379 ML/year (100 MMGPY) corn- or corn stover-based ethanol production. In general, the FTL scenarios have smaller capacities because the fuel yield of the used reference process designs is lower than in the alcohols producing processes. Also, notable is that lignin-based scenarios have a high production capacity; This is based on the assumption that almost all available lignin of black liquor can be separated and replaced by some other fuel and the cost of this replacement is included in the cost of lignin feedstock.

The capital intensity of biochemical scenarios seems to be higher than the capital intensity of thermochemical scenarios, however, with bigger production capacities and/or with higher yield they are comparable with thermochemical scenarios (e.g., scenario 41 has one of the lowest capital intensities (see Table IV)). One of the highest capital intensities is in near-neutral value-prior-to-pulping (VPP) process; this is partly due to very low ethanol yield and it can be offset by revenues from by-product (acetic acid).

The range of ethanol production variable costs is 0.2–0.7$/L (GEq) and 0.6–2.6$/L (GEq) for thermochemical and biochemical scenarios respectively; mixed alcohol variable production costs range from 0.4$/L (GEq) to 0.6$/L (GEq); and Fischer-Tropsch fuels variable production costs vary from 0.5$/L (GEq) to 1.0$/L (GEq). Among the thermochemical ethanol production scenarios, syngas fermentation has lower variable costs but much higher capital investment costs. For alcohol production, steam reforming scenarios seem to have both lower variable and capital investment costs, leading to higher profitability. These values compare well with values reported by Laser et al.:[20] biochemical production of ethanol + co-products have a total capital investment of 0.69–1.02$/annual litre GEq and operating costs of 0.69–0.88$/litre GEq using switchgrass feedstock with a biomass capacity of 4535 bdt/day. Also FTL production scenarios have similar results, a capital investment of 1.36$/annual litre GEq and an operating cost of 1.4$/litre GEq—in this study corresponding values are between 1.6 and 2.8$/annual litre GEq for capital investment and 0.5 and 1.0$/litre GEq for variable costs.

By-product credits are highest in acidic hydrolysis scenarios due to assumed significant production of the by-product furfural. FTL scenarios also have relatively higher by-product credits than alcohols producing scenarios because a fair part of the feedstock is converted to energy products (mainly natural gas replacement) and process heat is recovered and used in power production. This is also seen as low FTL yield.

The processing efficiency of the considered scenarios ranges from 23% to 51% for ethanol production scenarios. Up to 91% efficiencies are obtained for VPP and corn

Table IV. Biofuel scenario definitions and cost and profitability information.

	Products (process)[ref]	Feedstock[a]	Capacity (ML/year)[b]	Yield (L/bdt)[c]	Processing efficiency (%)[d]	Capital investment ($/L GEq)[e]	Variable costs ($/L GEq)[f]	By-product credits ($/L GEq)[g]	After-tax IRR (%)[h]
1	Ethanol + higher alcohols (gasification)[13]	B	95	338	51	3.3	0.3	0.2	−5.4
2	Ethanol (gasification + fermentation)[15]	B	95	338	43	4.0	0.1	0.2	−9.0
3	Ethanol + higher alcohols (steam reforming)[12]	B	95	338	51	1.8	0.2	0.1	5.9
4	Ethanol (steam reforming + fermentation)	B	95	338	43	4.7	0.1	0.2	−10.4
5	Mixed alcohols (gasification)[13]	B	95	397	53	2.8	0.3	0.1	−2.7
6	Mixed alcohols (Steam reforming)[12]	B	95	397	53	1.5	0.2	0.0	8.7
7	FTL (gasification)[13]	B	95	237	79	2.3	0.3	0.2	0.6
8	FTL (steam reforming)[12,16]	B	57	133	68	2.8	0.4	0.4	−1.4
9	Ethanol (acid hydrolysis)	B	95	130	25	5.7	1.5	1.7	—
10	Ethanol (enzymatic hydrolysis)	B	57	179	23	4.3	0.8	0.5	—
11	Ethanol + higher alcohols (gasification)	P	189	345	51	2.7	0.5	0.2	−11.4
12	Ethanol (gasification + fermentation)	P	189	345	43	3.3	0.4	0.2	−15.4
13	Ethanol + higher alcohols (steam reforming)	P	189	345	51	1.5	0.4	0.1	0.0
14	Ethanol (steam reforming + fermentation)	P	189	345	43	3.9	0.3	0.2	−16.4
15	Mixed alcohols (gasification)	P	189	405	53	2.2	0.4	0.1	−7.7
16	Mixed alcohols (Steam reforming)	P	189	405	53	1.2	0.4	0.0	3.4
17	FTL (gasification)	P	189	242	78	1.6	0.5	0.2	−2.4
18	FTL (steam reforming)	P	95	136	68	2.4	0.8	0.4	−9.1
19	Ethanol (acid hydrolysis)[10]	P	189	160	31	4.1	1.7	1.4	—
20	Ethanol (enzymatic hydrolysis)[11]	P	189	254	32	2.4	0.9	0.4	−21.5
21	Ethanol (acidic hemicellulose extraction)[11,17]	H	38	409	77	4.0	0.4	0.2	−6.8
22	Ethanol + acetic acid (near-neutral hemicellulose extraction)[11,18]	H	19	232	57	4.7	0.7	1.2	6.9
23	Ethanol + higher alcohols (gasification)	L	189	477	51	2.3	0.3	0.2	1.5
24	Ethanol (gasification + fermentation)	L	189	477	43	3.2	0.1	0.1	−3.7
25	Ethanol + higher alcohols (steam reforming)	L	189	477	51	1.2	0.2	0.1	12.3
26	Ethanol (steam reforming + fermentation)	L	189	477	43	3.6	0.1	0.1	−4.8
27	Mixed alcohols (gasification)	L	189	561	53	1.9	0.4	0.1	−20.6
28	Mixed alcohols (Steam reforming)	L	189	561	53	1.0	0.3	0.0	−10.3
29	FTL (gasification)	L	57	335	70	2.7	0.3	0.2	−4.8
30	FTL (steam reforming)	L	57	188	68	2.4	0.7	0.4	−9.7
31	Ethanol (enzymatic hydrolysis)[19]	C	379	424	91	0.7	0.6	0.1	−4.7
32	Ethanol + higher alcohols (gasification)	CS	379	269	51	2.5	0.5	0.3	−10.4
33	Ethanol (gasification + fermentation)	CS	379	269	43	2.9	0.4	0.2	−13.0
34	Ethanol + higher alcohols (steam reforming)	CS	379	269	51	1.4	0.3	0.2	3.4
35	Ethanol (steam reforming + fermentation)	CS	379	269	43	3.4	0.3	0.2	−14.4
36	Mixed alcohols (gasification)	CS	379	315	53	2.1	0.4	0.2	0.7
37	Mixed alcohols (Steam reforming)	CS	379	315	53	1.1	0.3	0.1	13.0
38	FTL (gasification)	CS	189	189	86	1.8	0.4	0.3	0.2
39	FTL (steam reforming)	CS	95	128	83	2.4	0.5	0.4	−0.2
40	Ethanol (acid hydrolysis)	CS	379	179	44	3.1	1.2	1.0	−22.5
41	Ethanol (enzymatic hydrolysis)[4]	CS	379	341	55	1.2	0.5	0.2	0.3
42	Ethanol (enzymatic hydrolysis)	FW	19	235	51	2.4	0.8	0.1	−2.7

[ref] The reference(s) used for process design and product yields.
[a] B = woody forest based biomass, P = pulp wood, H = extracted hemicelluloses, L = separated lignin, C = corn grain, CS = corn stover, FW = food processing wastes.
[b] Production capacity of the main fuel in million litres gasoline equivalent per year.
[c] Main fuel yield in litres per bone dry ton of feedstock; reference values converted to yields of non-reference designs based on higher heating values: $HHV_B = 18.4$ MJ/kg, $HHV_P = 18.8$ MJ/kg, $HHV_H = 12.5$ MJ/kg, $HHV_L = 26$ MJ/kg, $HHV_{CS} = 14.6$ MJ/kg, $HHV_C = 17$ MJ/kg.
[d] Energy out as percent of feedstock higher heating value, used heating values: $HHV_{Ethanol} = 29.7$ MJ/kg, $HHV_{MA} = 31$ MJ/kg, $HHV_{FTL} = 46.2$ MJ/kg (diesel), $HHV_{Acetic\ acid} = 19$ MJ/kg, $HHV_{Furfural} = 19$ MJ/kg, $HHV_{DDGS} = 17$ MJ/kg.
[e] Total capital investment cost per litre of main fuel gasoline equivalent (GEq), $HHV_{Gasoline} = 47.3$ MJ/kg.
[f] Operation and maintenance costs per litre of main fuel gasoline equivalent (GEq), includes feedstock and other variable costs.
[g] Credits from by-products per litre of main fuel gasoline equivalent (GEq): fossil fuel savings due to excess heat from biorefinery process; excess electricity; DDGS, acetic acid, furfural; higher alcohols (methanol, propanol, butanol).
[h] Expected after-tax IRR value calculated based on assumptions in Table I using Monte Carlo analysis, dash denotes very low profitability.

scenarios: both have high sugar content raw material and therefore high fuel and by-product yields are possible. The lowest ethanol scenario processing efficiencies are for enzymatic hydrolysis options whereas all thermochemical options have similar efficiencies. FTL and MA scenarios have relatively high processing efficiencies than ethanol production scenarios because of higher product yield and in FTL case by-product yield.

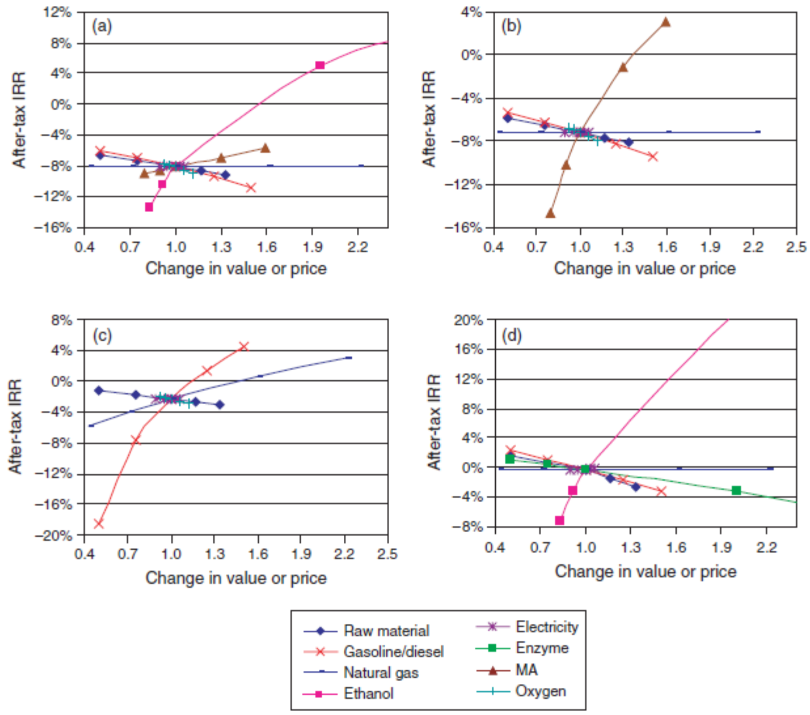

Fig. 3. Illustrative example of sensitivity analysis results: Profitability as a function of change in sensitivity analysis variable. Value 1 denotes the base case values given in Table II. (a) Woody biomass-to-ethanol (gasification + mixed alcohol synthesis), (b) Woody biomass-to-mixed alcohols (gasification), (c) Woody biomass-to-FTL (gasification), and (d) Corn stover-to-ethanol (enzymatic hydrolysis).

2.2. Sensitivity Analysis

Main cost model variables were varied in the sensitivity analysis. The range of variation was based on historical data, or model and input data uncertainty (e.g., enzyme cost 0.05–0.3$/gal ethanol). Four representative sensitivity analysis graphs are shown in Figure 3. Other feedstocks have similar sensitivities when considering the same or similar process options.

From Figure 3 it can be concluded that the main end-product price has the biggest impact on profitability in all scenarios (gasoline price represents FTL prices). Also the by-product price is important in all cases having by-products, e.g., FTL-scenarios produce tail-gas which can replace natural gas from lime kiln. The feedstock crop price has relatively similar impact on all scenarios. Enzyme cost in biochemical scenarios is also important due to its relatively large range compared to any other variable. Also, thermochemical scenarios are sensitive to oxygen cost, however, the range of oxygen cost is relatively small and therefore the impact is not significant (in this study, an air separation unit (ASU) is used in all scenarios; such a system is described by Larson et al.[13]).

Gasoline and diesel prices have a very important role in profitability of all fuel production scenarios. This is due to two reasons: gasoline is used as denaturant of fuel grade ethanol (5 volume-%) and transportation cost of raw material is highly dependent on fuel price. Although ethanol and mixed alcohol price trends are assumed in this study to be correlated with the gasoline price trend, in sensitivity analysis this correlation is not considered.

2.3. Risk Analysis

The main variables having impact on profitability identified in the sensitivity analysis, including prices of raw materials and end-products, were selected for risk analysis. Additionally, energy prices (price of gasoline/diesel and natural gas) were considered in the risk analysis because they define the prices of end-products and partly also the prices of delivered raw materials. Prices are assumed to have the same volatility and probability distributions as their historical values (in 2008 real-$). The future price trends are addressed by using published energy price forecasts: Fossil fuel trend forecasts by U.S. Department of Energy (DOE) and Energy Information Agency (EIA)[21] are converted to ethanol, FTL and MA price forecasts using higher heating values. A triangular probability distribution with highest probability for reference price trend was set. Similar price trends were then defined for woody biomass and agricultural waste feedstocks that are assumed to have price increases in the future. The high cost trend was set based on an estimate that their prices would not exceed current pulp wood price during the forecast period. Other feedstock prices (in 2008 real-$) were kept constant.

Using the defined probability distributions of prices and their future trends a Monte Carlo analysis was carried out. The profitability distributions resulting from the risk analysis (5000 iterations) are shown in Figures 4 and 5 for thermochemical and biochemical scenarios respectively.

Based on Figure 4 and the last data column of Table IV, corn stover and woody biomass scenarios have similar behaviour in all thermochemical scenarios, even though their prices and process yields are different. Also, the production capacities differ (i.e., corn stover-to-ethanol or MA 379 ML/year whereas biomass-to-ethanol or MA is only 95 ML/year). These raw materials also have narrower IRR probability distributions; hence, they are not as risky feedstock options as pulp wood or lignin. Lignin in ethanol production scenarios is profitable; however, its availability with the assumed high capacity needs a more refined analysis.

Product-wise, it seems that ethanol production is not as risky as MA or FTL production. However, MA production

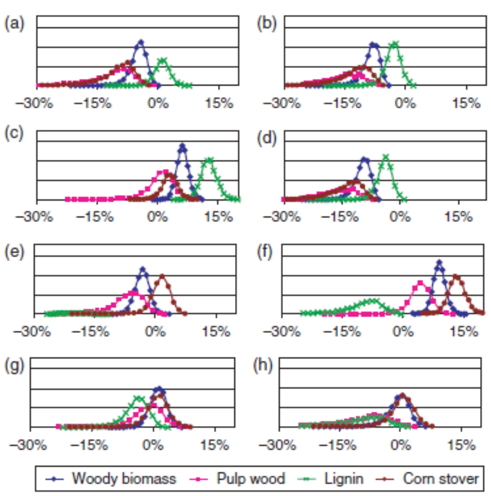

Fig. 4. Probability distribution of after-tax IRR of thermochemical biofuel production scenarios: (a) Ethanol (gasification + MA synthesis), (b) Ethanol (gasification + syngas fermentation), (c) Ethanol (steam reforming + MA synthesis), (d) Ethanol (steam reforming + syngas fermentation), (e) MA (gasification + MA synthesis), (f) MA (steam reforming + MA synthesis), (g) FTL (gasification), and (h) FTL (steam reforming).

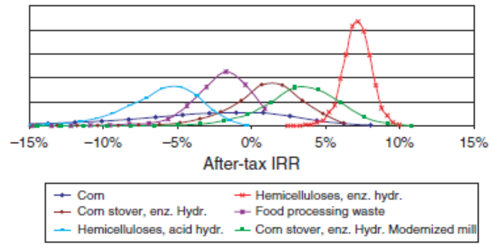

Fig. 5. Probability distribution of after-tax IRR of biochemical biofuel production scenarios.

from woody biomass or corn stover using steam reforming process (Fig. 4(f)) seems to have a higher profitability than any other ethanol production scenario, even considering the downside (worst case scenario) profitabilities. This process (steam reforming + MA synthesis) seems to be most promising because upgrading the mixed alcohols from the same process to ethanol (Fig. 4(c)) has second highest profitability.

All biochemical scenarios are not shown in Figure 5 due to their very low profitability (mean value $< -10\%$, Table IV). Notable here is that corn as feedstock seems to be a very risky solution and the profitability of that scenario is also much lower than was reported in the preliminary results in Hytönen and Stuart.[8] This results from validation and updates of price assumptions. The "riskiness" of the corn-scenario results partly from the assumed corn and ethanol price trends over the life-time of the plant, and partly from the process design (no diverse revenue base). Other feedstocks (even though ethanol yield is lower) have more stable revenues from by-products and they are not dependent on fossil fuel based energy and are therefore not as risky solutions.

Biochemical scenarios using forest based feedstocks are clearly not profitable under the case study assumptions. Even with the beneficial impact of pulp mill modernization which was discussed in Hytönen and Stuart[8] these scenarios are not comparable with the scenarios shown in Figure 5. However, pulp mill modernization slightly increases the profitability of corn stover scenario slightly.

2.4. Screening out Non-Promising Design Options

The results of the Monte Carlo analysis show that some scenarios are not profitable under the defined economic scenarios and price trends, and they can be automatically screened out. Based on the profitability probability distributions, the most promising design options are corn stover-to-mixed alcohols using steam reforming followed by mixed alcohol synthesis and lignin-to-ethanol using steam reforming followed by mixed alcohol synthesis and ethanol separation. The most promising biochemical process option is the near neutral hemicellulose extraction

Table V. Most promising design scenarios based on screening.

#	Product (process)	Feedstock	Capacity (ML/year)	Total project investment (M$)	IRR (%)	Standard deviation of IRR -σ (%)
37	Mixed alcohols (steam reforming)	CS	379	308	13.0	2.1
25	Ethanol + higher alcohols (steam reforming)	L	189	159	12.3	2.0
6	Mixed alcohols (steam reforming)	B	95	99	8.7	1.6
22	Ethanol + acetic acid (near-neutral VPP)	H	19	61	6.9	0.9
3	Ethanol + higher alcohols (steam reforming)	B	95	117	5.9	1.5
34	Ethanol + higher alcohols (steam reforming)	CS	379	364	3.4	2.0

scenario because it is less risky and has higher expected IRR than other scenarios. The list of most promising scenarios ranked based on after-tax IRR is shown in Table V.

The most promising scenarios also seem to be relatively risky (variability ~2%). On the other hand, their worst case profitability is still relatively high compared to expected profitability of the next best scenarios. For example, the 95% confidence interval (~2σ) of the most promising scenario is 9%–17% from which the downside IRR, 9%, is still higher than the expected IRR of third most promising scenario. It must however be noted that if a capital investment limit exists, this list might not include some of the high capital cost scenarios such as the high capacity corn stover (CS) scenarios.

2.5. Impact of Subsidies

Several types of governmental and regional subsidy/incentive programs are in force at the moment and possibly also in future, in order to enhance the competitiveness of lignocellulosic biofuel production compared with fossil and corn based fuels. Especially volumetric and small producer excise tax credits could provide the producer/retailer with substantial additional revenues, however many of the programs are planned to last only for a short time period (few years) and are different for each product. For this "uncertainty" of long term production related incentives it is not rational to rely on them in profitability estimation and in early stage comparison of scenarios.

As an example, the profitability of the most promising scenario under hypothetical 9.4 ¢/L GEq fuel (volumetric excise tax credit, 50 ¢/gal MA) over the project lifetime would increase to 22% from the 13% in the base case. Another type of incentive, a further accelerated depreciation system such as 50%–25%–25% (instead of the 7 year Modified Accelerated Cost Recovery System (MACRS) used in base case) would enhance the profitability if debt is taken for the investment project: the faster depreciation results in an earlier positive cash flow after start-up bringing therefore savings from interests. Project financing issues were not considered in this study.

3. CONCLUSIONS

A techno-economic assessment with Monte Carlo risk analysis of different biofuel production scenarios integrated into a North American hardwood pulp and paper mill was conducted.

In the case of biofuel production, the end-product price is the most important variable of the profitability of integrated forest biorefinery scenarios. The feedstock crop price, even though important, is not as critical from the profitability point of view. However, because transportation costs are a substantial part of the raw material total cost the combined impact of fuel prices and crop cost can be comparable with the impact of end-product price.

Under the economic assumptions used in this case study, corn stover-to-mixed alcohols and lignin-to-mixed alcohols and ethanol are the most promising and un-risky design scenarios. In the lignin using scenario, lignin separation from black liquor is assumed to be possible in large quantities (almost all lignin of mill black liquor) and with low cost (separation costs assumed to be included in lignin price). The most promising biochemical process option is near-neutral hemicellulose extraction scenario.

The additional knowledge resulting from sensitivity and risk analyses enables more certain screening out of non-promising scenarios because of the definition of downside profitability of the most promising scenarios in addition to the expected profitability value.

The plant capacities selected for lowest production cost capacities are based on calculations with a few possible capacities over a wide range of capacities. Also, the factorial design approach does not consider possible needed design changes due to scaling the reference design capacity to substantially different capacity leading to step-wise investment cost curve (as a function of capacity). Mathematical programming might also propose different minimum manufacturing cost capacities. However, it was not the purpose of this study to design the final processes, rather to define relatively correct, comparable design options, for which the used approach gives sufficient results.

4. IMPLICATIONS

It is clear from the results that the scenarios can be ranked based on only one economic measure, e.g., after-tax IRR. In addition, in this case study, risk analysis has a substantial impact on screening, especially related to corn ethanol scenario: high uncertainty in the profitability, even though

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the expected value is comparable with other promising scenarios, lowers its attractiveness as a biorefinery solution at the case study mill. Furthermore, risk analysis enhances the understanding of the decision making context. To further enhance the decision making, it would be reasonable to also use other economic measures in addition to profitability measures, e.g., total capital investment. This was not done in this case study.

Based on this profitability assessment, it can be concluded that steam reforming followed by mixed alcohol synthesis and ethanol separation (products: ethanol and higher alcohols) and steam reforming followed by mixed alcohol synthesis (product: mixed alcohols), are in general the most promising process designs with all available raw materials. On the other hand, agricultural lignocellulosic wastes have best economic performance among the studied feedstocks for both thermochemical and biochemical biofuel production. Forest based lignocellulosic raw materials are only competitive if thermochemical processes are used.

Mixed feedstock scenarios were not examined in this case study; however, they could be assessed with the used analysis method. If the designed process can use mixed raw materials it can enhance the profitability of the design by lowering the raw material costs. On the other hand, some additional investment costs might be associated with these scenarios and even separate process lines or parts of the processes might be required in order to be able to produce same product from two or more raw materials. For example, combination of two biochemical scenarios using C5 and C6 sugars originating from hemicellulose extraction and woody biomass respectively might need separate hydrolysis and fermentation steps but could use the same end product purification process.

For biochemical processes to be more attractive for investors, the sensitivity analysis shows that only higher product prices can achieve better profitability. Currently, and perhaps also in the future, government incentives and subsidies can help with this. However, in the long term, technology and crop development should play a big role in lowering the capital intensity of biochemical processes. Especially if only fuel production is pursued, this might be the only option to increase profitability, since raw material cost will most probably increase with fuel price increase and subsidies are not a long term solution.

To diversify the biorefinery product portfolio to include higher value-added products besides the biofuels is gaining more and more interest. This can also increase the overall profitability, however, technologies for the production of green chemicals and materials as well as markets for them still need some time to develop. Also, different fuel production platforms examined in this study have different potential in terms of value added products: for example, the FTL process could be modified to produce a higher amount of higher molecular weight hydrocarbons (waxes) by using a suitable catalyst in synthesis. These waxes could be sold to wax markets instead of cracking them to diesel and selling as fuel. They have relatively high value even when compared with petroleum based waxes due to their controllable properties that enable their use in several applications; hence, if this product portfolio would be selected for the FTL IFBR the profitability of the FTL scenarios would be enhanced substantially. Assessing the potential of all studied scenarios and using this information as additional decision making criteria should therefore be considered.

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APPENDIX C – Article: Operations-driven cost-impact evaluation of kraft process retrofit projects for capital appropriation: case of forest biorefinery

Operations-driven cost-impact evaluation of kraft process retrofit projects for capital appropriation: case of forest biorefinery

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Abstract

Increased interest of the forest products industry in revenue diversification through biorefinery implementation has lead to efforts in product portfolio and process design, and technology evaluation in order to identify the best investment strategies for a specific site. The focus has mainly been on evaluating the new product manufacturing lines under constraints posed by the existing production system. However, the impacts of the investment on the existing products' cost competitiveness can potentially be an even more important factor for success than the new product's profitable production based on analysis in isolation can reveal.

This article proposes a methodology based on advanced costing principles and process design methods to examine the cost implications of the retrofit modification of an existing continuous processing facility. The methodology is applied to pulp and paper mill retrofit projects. The cost impacts of particular interest are changes in overhead, labour and joint activity costs and costs in a volume-flexible production setting. The results clearly show that the production costs of the core-business product differ between retrofit projects resulting from systematic cost allocation and assignment and plant-level cost accounting instead of traditional engineering cost evaluation. Moreover, the overall margins, product profit margins and contribution margin can support the capital appropriation by showing the forest biorefinery (FBR) performance under expected future business environment changes.

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Keywords: operations-driven costing; activity-based costing; process design; retrofit; forest biorefinery

1 Introduction

The pulp and paper (P&P) industry extensively uses steady-state process simulation to analyse existing processes. The resulting mass and energy (M&E) balances are used in decision making as the basis for techno-economic analyses. Furthermore, management evaluates manufacturing costs at least on monthly and annual basis using different cost accounting methods. These methods use inventories and data from information management systems to calculate financial statements.

These two separate cost evaluation activities both have their specific purposes and therefore their strengths: the engineering evaluation process is based on process understanding and has better accuracy in resource consumption, cost accounting on the other hand is strong in the calculation and allocation of non-production costs such as facility and corporate overhead and labour costs, and the derivation of meaningful measures of performance for management. A systematic link between them could potentially improve the decision making in the early stages of retrofit capital appropriation. This results from formal translation of the constraints and opportunities of the existing processes and business to the performance of the investment project and the new transformed business.

This paper proposes a novel framework that combines relevant process design methods and cost accounting principles for evaluation of retrofit capital spending strategies. In the first section, the economic analysis literature relevant for retrofit process design and strategic capital spending decision making is reviewed. The next section states the specific objectives of this research. Then the proposed methodology and the case study are presented. In the results and discussion section different important cost implications of retrofit projects are demonstrated, specifically focusing on quantifying the cost impacts of retrofitting on 1) core business production costs, and b) marginal costs. Production costs in volume-flexible production system are also addressed. Finally, the paper concludes with describing potential extensions and uses of proposed methodology.

2 Background

Cost analysis research is reviewed from two perspectives: 1) how management uses costing to make capital expenditure and operating decisions, and 2) how engineering process design evaluates O&M costs for decision making. This helps to arrive at an understanding of current capital spending planning related costing capabilities.

Several surveys have reviewed industry practices in capital investment decision making. Farrager et al. (1999) surveyed 379 U.S. based companies' entire investment decision making process without explicitly looking into accounting methods that the companies use. The answers imply that almost all companies evaluate somehow at relatively detailed level the resulting operating costs of an investment project in order to arrive at forecasts of annual operating cash returns, changes in working capital and their residual cash flows. Similar implications arise from other capital budgeting research (e.g. Hogaboam and Shook (2004)). Furthermore, a key requirement arising from the industrial context is a better understanding of the impacts of possible changes in the business environment on these forecasts (and capability of retrofitted facilities to perform under the changing conditions) and it is noteworthy to review also some relevant operations research concepts.

2.1 Management cost analysis

2.1.1 Product costing

Traditional costing methods are used commonly in all industries. These costing methods are mainly designed for reporting financial accounts at the end of a reporting period. They are based on assigning total costs incurred during the period (measured from changes in raw material inventory levels and purchased raw materials through the period of analysis) using plant-wide blanket rates and average production rates to obtain product costs. Depending on the production system (single product or multi-product) and bases for allocation and assignment rates it can lead to significantly differing costs from the "true" product costs.

An enhanced traditional costing method, and also a predecessor of activity based costing (ABC), is functional-based costing (FBC). In FBC the costs are allocated and assigned at unit-level (a unit is defined as the production line of a product, for a single-product facility the facility is the unit) and then aggregated into the facility level for reporting and analysis. The allocation rates are measured with production rates, direct labour hours or machine hours. Hence, cost pools are first consumed by facility units or departments and these units are consumed by products, instead of assigning all costs directly to end products. The allocation of all costs with unit-level drivers (including non-unit related overhead costs such as setup costs or grade change costs or seasonal maintenance or corporate overheads) can distort the product costs if non-unit-level overhead costs are a relatively significant part of the total overhead costs and if different products produced in a unit have different overhead activity demand.

In ABC also the non-unit-level drivers are defined and therefore it should lead to product costs that are closer to the true costs. Cooper and Kaplan (1988; 1991) describes ABC as a more correct means for product costing in today's industry setting (large companies) where expenses covering marketing, distribution and support have a significantly increased proportion of the total costs compared to traditional direct labour and material costs and the costing method should be able to properly allocate overhead cost. Moreover, when multiple products are produced simultaneously, ABC can enhance the cost estimates. For example, Wang et al. (2008) report the implementation experiences of ABC in the Chinese refinery industry to better cost the intermediate products in addition to the final products. A theoretical proof of cost accuracy has also been studied by Charles and Hansen (2008) using game-theory concepts for comparing FBC and ABC in product costing. They conclude that theoretically ABC yields product costs relatively closer to the true costs if there is sufficient product diversity (the product's consumption of the individual cost pools are sufficiently different, thus the individual unit-level drivers of FBC differ enough from the activity drivers of ABC).

Brierley et al. (2006) investigated the product costing practices in discrete manufacturing and continuous process industries using a survey. Although ABC is not a major costing method in this type of industries based on this study, there does not seem to be any significant difference between practices in these different industries. Differences however exist in the bases for activity and resource driver definitions: continuous process industries use production rate and time as driver performances more often instead of direct labour.

Utilisation of advanced costing methods in capital spending decision making has also been studied. Angelis and Lee (1996) proposed a methodology for utilising ABC already adopted for accounting in a company as a costing model for evaluating cost impacts of investment strategy on individual activities. These impacts, or changes in resource costs due to investment, are aggregated into overall impact using ABC and then used in analytical hierarchy process -based decision making. Sawhney (1991) used activity-based modelling to evaluate investments' performance related to manufacturing strategy components (e.g. capacity, productivity, lead time, quality). Measures of performance are often based on costs at the activity level, thus a form of ABC was needed. The methodology presented in this research linked the activity-based modelling to investment selection and evaluation at different phases of the investment process also using multi-criteria decision making methods.

The use of ABC has been extended from an investment project analysis to life-cycle costing (LCC) for example by Emblemsvåg (2003) or Rivero et al. (2007). They have used ABC to evaluate life-cycle costs of different long-range scenarios (budgeting scenarios) of a facility or a company to identify key success factors of scenarios for better informed comparison.

Greenwood and Reeve (1992) have also criticized the use of traditional ABC in operational decision making. They recognized the pooling of costs based on an activity driver as a limitation of standard ABC, if however the pooling was done based on process this would significantly enhance the management's understanding of *process costs* and lead to a better capability to continuously improve processes.

Thus, it can be concluded that ABC as accounting method in the specific context of FBR (multi-product and continuous process system) should yield better cost information than traditional accounting methods. It could also potentially help already in early stage retrofit design decision making context to accurately evaluate production costs, especially if it has already been adopted as accounting method in the company.

2.1.2 Cost analysis in operational planning

Costing has also a significant role in operational decision making. Product pricing and add/drop decisions are often done partly based on costs of production. In a study by Paul and Weaver (2002), relevant costs and appropriate measures for this particular decision making context are examined. Their survey showed that several methods are often used in parallel: full standard costing, direct standard costing, incremental cost analysis or different mark-up evaluation. Although short-term decisions should be based on a contribution margin or variable costs and long-term decisions based on full standard costing (FSC), many of the survey recipients are not following this norm of microeconomics (fixed cost of capacity is a sunk cost and non-relevant for operation decision making). Rather, due to various management practices even opposite methods are used to guide decision making. Based on this, it is critical to better understand the relevant costs for a particular product decision and keep in mind the possible long-term impacts of short-term decisions.

Panzar and Willig (1977) defined the concept of *economies of scope*, a reason for companies to produce multiple products in one facility/company and benefit from the co-utilization of physical assets and know-how in production of all the products. Even though not applicable to all cases the concept can help in understanding what costing methods best applies in an operations decision making context. Kee (2008) further concretizes the differences between marginal and full costing methods under economies of scope conditions for pricing, product mix and capacity related decisions, and Haka et al. (2002) examined the impact of allocation of fixed costs, or different costing principles, in the same decision making context under oligopoly market conditions.

2.1.3 Marginal costing

An example of relevant cost analysis is marginal costing. Almost all continuous production systems are somewhat volume-flexible which enables short-term changes in production volume from design capacity to supply the changing demand of products or to react to attractive market prices. The relevant costs in this case are variable costs and an often used measure is the marginal cost (MC) of product *i* or the cost of one additional unit of product *i* more produced:

$$MC_i = \frac{dTC_i}{dQ_i} = \frac{d(FC_i + VC_i)}{dQ_i} = \frac{dVC_i}{dQ_i} \qquad [1]$$

where Q_i is the flow of product or intermediate *i*, TC_i, FC_i and VC_i are the total, fixed and variable costs of producing product *i*.

Another measure is the contribution margin (CM):

$$CM_i = R_i - VC_i$$
$$CM = \sum_i CM_i \qquad [2]$$

where R_i is the unit revenue (or price) of product *i*. This shows how an increase in production translates to profits, and thus is able simultaneously consider marginal costs and marginal revenues. This can also be aggregated into one contribution margin mark-up to measure the overall operating leverage of the facility and it can be measured as the percentage of either revenue or variable costs or as absolute value as in equation 2.

When using equations 1 and 2 it is important to include in the variable costs possible changes in other products' variable costs as those are relevant costs to the production rate change. Furthermore, if the operating point is expected to differ from the design point for a longer period of time, also fixed costs should be included in the decision making and thus full costing is preferred.

Kloock and Schiller (1997) investigated the use of marginal costs in short- and long-term decision making to compare it with ABC as a decision making basis. By definition, marginal costs are assigned by the *cause and effect* principle, whereas in ABC assignment is based on *demand*. This leads to the fact that in ABC the short-term fixed costs are also assigned to products (services etc. are required in order to produce the product) but in marginal costing since the additional products produced do not cause change in services etc., their cause (fixed cost) is not relevant. Based on the analysis of both methods in product pricing, the same solution is obtained, thus no difference in the pricing decision should occur if ABC is correctly implemented.

2.2 Cost analysis in process design

Unlike in accounting, cost analysts in process design traditionally focuses on capital investment cost evaluation and not on operating and maintenance (O&M) cost estimation. Different design phases have standard capital cost estimation methods that are described in every engineering handbook (e.g. Peters et al. (2003) or Seider et al. (2009)). However, only very little attention is given to O&M cost analysis and it is common practice to use simple parametric models, for example a fixed percentage of capital costs.

Overall methodologies focusing more on O&M cost analysis in continuous process industries have been proposed, e.g. Sadhukhan (2008; 2007) developed a process synthesis methodology for retrofit process design based on value analysis where mathematical programming is used for obtaining optimal process design. The costing method approaches each process element from both raw material and end-product directions simultaneously in order to arrive at the values and costs of streams using directed graphs. Cost allocation between multiple outputs of a process element is not considered explicitly, all products of an element are given same cost of production. Janssen (2008; 2007) developed a retrofit design decision making framework based on ABC and demonstrated the methodology in the context of increased deinked pulp production and cogeneration at an integrated newsprint mill. A single-product and multi-feedstock system was considered. The cost model driver performances were linked to the mill information management system when appropriate and production functions were used to estimate drivers that needed to be calculated from available data (e.g. new processes introduced by the retrofit design scenarios).

Marginal costing is also presented by some authors as a costing method for process design: Hui (2000) introduced a linear programming based marginal value analysis method. It was concluded that the knowledge of all intermediate stream marginal values can help to decide whether some intermediate streams should be purchased or produced or sold without further processing them. Li and Hui (2007) applied the same method to a refinery planning context and extended the estimated marginal impacts from the initial solution point to a wider range of points in the solution space by using sensitivity analysis and parametric programming. Janssen (2008) illustrated the marginal costs of energy and marginal impacts of production rate change on project profitability in forest industrial context. These results indicated that system constraints govern in that specific context. Varbanov et al. (2004) and Smith and Varbanov (2005) also utilise marginal cost analysis in a top-level analysis methodology (developed by Makwana et al. (1998)) which calculates the true cost of utilities and is specifically targeted at the identification of potential retrofit energy projects.

Sandström (1999a; 1999b) investigated especially the fit between ABC and engineering design and how ABC system should be constructed to be used in product costing in process design. The survey conducted with design engineers of case examples indicated that costs structured using ABC and activity chains are informative and useful for them. It is also concluded that ABC is well suited for early stages of design.

In summarizing the literature, depending on the market type the company is considering to enter (or to stay in) with the retrofit capital investment project, relevant cost factors should be considered by accountants and management in analysis and decision making. Therefore, also suitable costing methods should be selected. However, research shows that the same results should be obtained independent of costing method (variable costing vs. full costing).

The engineering cost analysis for retrofit capital spending is often done without detailed O&M cost information and accounting methods and thus can potentially miss critical cost changes especially related to fixed costs. In addition, the engineering design economic analysis is not linked to management decision making to the maximum extent. Thus, appropriate costing methods that better integrate design analysis and management decision making are needed, and these methods should be able to illustrate the potential of the retrofit alternatives under a changing business environment. Specific to the retrofit context no comprehensive costing methods have been proposed.

3 Objectives

The objective of this paper is to demonstrate how by using existing management reporting and process analysis tools and methods the retrofit capital appropriation process can be enhanced. Sub-objectives linked to this are:

- To show how retrofit integration cost impacts can be quantified using operations-driven costing and how different cost allocation methods used in the industry manifest themselves in the cost analysis results
- To illustrate how marginal cost analysis capability can be utilised in the capital appropriation cost-benefit analysis of multi-product systems and what are the cost implications of production volume flexibility

A case study is used to illustrate the objectives.

4 Methodology

In the next sub-section, an overall retrofit project profitability analysis procedure is described to illustrate the overall context for cost analysis. The sub-sections after that define the actual costing methodology and the case study where it was applied.

4.1 Retrofit techno-economic analysis

A retrofit techno-economic analysis follows four key steps that aim at the construction of a systematic comparison framework:

1. Development of the base case
    a. Mass and energy balance simulation model development, or using existing plant-wide steady-state process simulation models
    b. Interfacing existing cost accounting models with the process simulation model. Operations-driven or activity-based costing systems are required.
2. Validation of the base case
    a. M&E balance validation under different running conditions of the plant
    b. Cost model validation, e.g. comparing model-based monthly financial statements with months' financial statements of the mill
3. Development of retrofit cases
    a. Development of process designs and their simulation models
    b. Integration of the new process simulation models into the base case model
    c. Updating the base case cost model to handle new resources and process departments of the retrofit cases
4. Techno-economic analysis
    a. O&M cost, marginal cost and capital investment cost analysis
    b. Sensitivity analysis
    c. Risk analysis (e.g. scenario analysis, Monte-Carlo analysis, law of propagation of error (LPE), etc.)

This kind of method or parts of it can be used consecutively with an increasing level of detail in capital appropriation as a means of obtaining decision making information. The application of the entire retrofit techno-economic analysis methodology is demonstrated by the authors elsewhere (Hytönen et al., 2010), the rest of this paper focuses on the costing method (three first steps of the above depicted methodology).

4.2 Operations driven cost analysis methodology

The proposed cost simulation method aims at better exploitation of existing operations-oriented analysis and reporting capabilities in a novel application.

In activity based costing, different types of drivers are utilized to describe the consumption of resources and activities (by other activities or cost objects), see Figure 1 a). For continuous and strongly interlinked and integrated processes the ABC-type definition of cost object and inter-activity activity-drivers can be re-defined (see Figure 1 b)) to better utilise the basis of these drivers: almost all activity-drivers in chemical processing plants are based on continuous material flows, e.g. by-product streams or very high pressure steam (VHP) and process steam, or bleached pulp. Some of the activities are also consumed in many of the other activities or departments. Converting the complex activity-driver matrix to a resource driver–like syntax enables easier tracking of changes in the costs. The intermediate resources are thus products produced by activities and their cost flows are defined based on the corresponding rule of allocation in the producing department.

Rapid analysis of several retrofit alternatives, such as forest biorefinery strategies, benefits especially from this approach: Adding new process sections and departments or modifying the existing mill configuration only requires addition of the new department blocks, the re-configured activity-drivers based on material or energy flow are automatically considered and there is no need to modify the driver sources or destinations. For example, adding a new steam turbine using the traditional ABC definition would require re-routing the VHP and process steam drivers between all old and the new departments. By using the proposed structure instead, the new steam turbine department consumes a pre-defined intermediate resource (VHP steam with a cost) and produces other pre-defined intermediate resources (process steams) and updates their cost flows accordingly. Thus, definition is done in similar manner as for fixed costs but driver basis is mass and energy balance.

When process conditions or design is changed, i.e. due to a retrofit project, the changed balance is automatically translated into costs through the model structure: drivers are formulated as a sparse matrix (each department or unit operation represents a vector in this matrix, consumed resources and intermediate resources have non-zero value) that is a result of the new process steady state. Similarly, the allocation table is a sparse matrix that accounts for cost transfer out from each department according to the products of that department. Cost flows with fixed unit cost (e.g. process water and waste waters that are passed between departments before sending them out from the facility) naturally pass part of the costs with them and are considered in the allocation as inward cost flow, depending on the level of detail and the purpose of the cost model the amount of these type of drivers may vary significantly. This sparse matrix formulation increases the computational requirement of the cost modelling but it is important to be able to quickly analyze significantly differing process configurations in the early stage of process design. Moreover, the time saved in not developing optimal cost models from computational standpoint for all designs is significantly higher than the computation time.

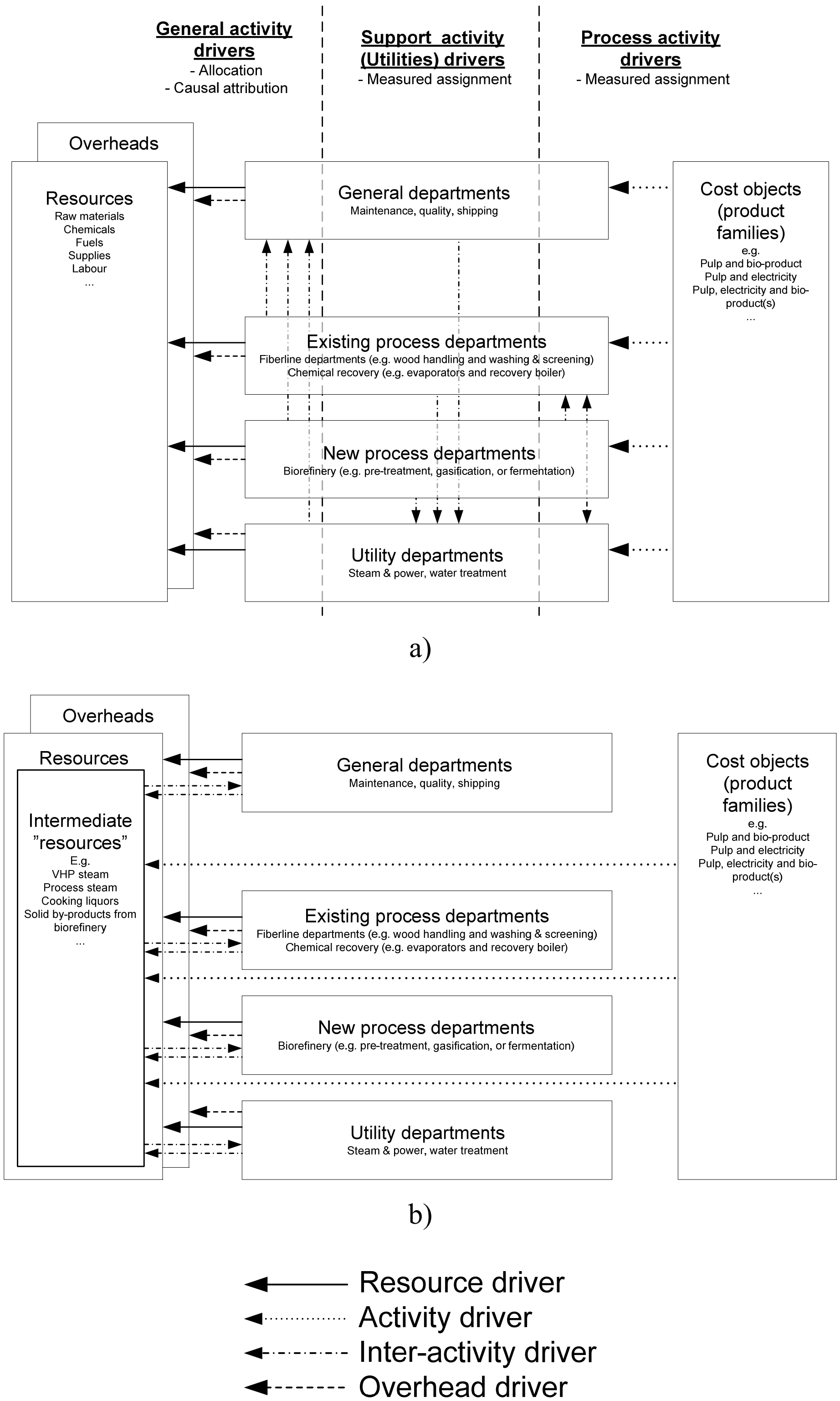

Figure 1. a) Definition of drivers in ABC costing, b) re-formulation of inter-activity activity-drivers for operations-driven costing for continuous multi-product facility

The structure of the cost model using this operations-driven costing framework based on separate but strongly linked process and cost simulations is illustrated in Figure 2.

- The process simulation model(s) provide steady-state information of the material and energy flow-based drivers. The balances are passed to the cost model through an interface (tool specific input/output methods should be utilized). Market understanding (both from mill specific contracts and bigger scale markets) defines the prices for a pre-defined time period as well as probability density functions (pdf) of price trends and values. Facility's current and historical performance and required actions to stay in business define historical and future fixed costs and capital spending (maintenance spending, annual capital spending in development and replacements), and company practices in cost allocation define different allocation bases.
- The cost model, like any ABC–type cost model, executes activities in a pre-defined order and cascades costs further. The costs of a department are separated into variable and fixed costs, these costs are then allocated to all cost-carrying products, and if these are intermediate "resources", the costs of those are updated in the intermediate cost tables accordingly. In the case of stochastic risk analysis, the cost model is executed as a sub-task of the risk analysis method. For example, if Monte-Carlo analysis is used, the model is re-calculated n times with randomly selected input variable values (n sets of input values, based on input value probability density function) to form output value probability distribution.
- As a result, all product costs (and intermediate resource costs) are obtained. Utilising Monte Carlo analysis or other methods for propagation of statistical error/variance also provides the pdf's of all production costs.

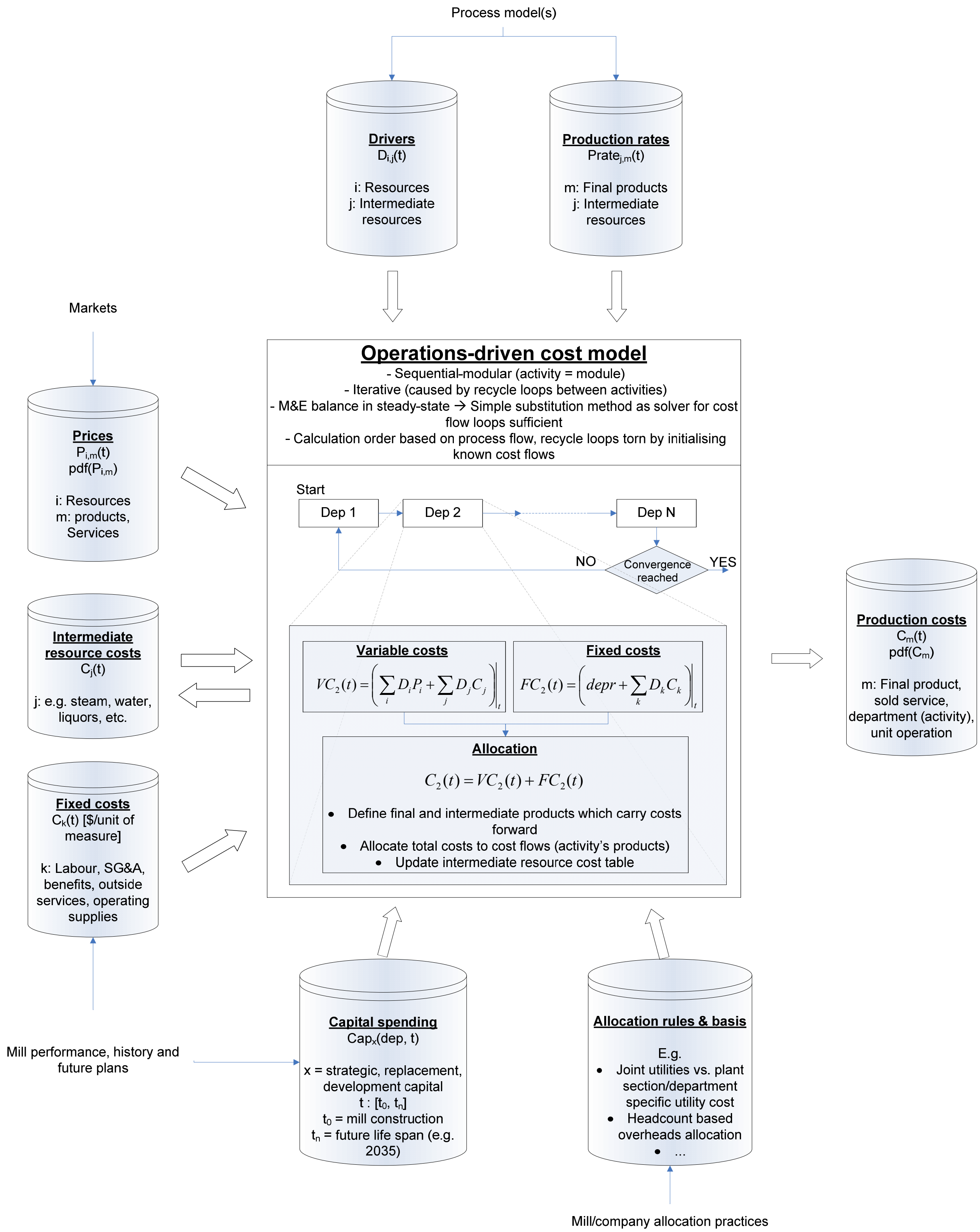

Figure 2. Generic structure of a cost model, based on proposed operations-driven cost modelling framework

4.3 Case study

The methodology was applied in a continuous manufacturing context, namely in a forest biorefinery context. A North-American integrated hardwood kraft pulp and paper mill, currently producing 1200 air-dry ton (adt) of pulp and 1600 bone-dry ton (bdt) of paper products from the pulp annually was used as the base case. Retrofit process design scenarios included one traditional project and two biorefinery implementation strategies. These were selected after pre-screening potential biofuel production alternatives and the most promising production capacities for the case mill (see Hytönen and Stuart (2009; 2010) for more information about the pre-screening step). Detailed base case mill and example retrofit scenario definitions are discussed in earlier work of the authors (Hytönen et al., 2010). In short, these are the retrofit project descriptions:

- Mill modernization – Current pulp production capacity is increased by 35%, requiring significant modifications in current process equipment and installation of new equipment.
- Corn stover-to-ethanol – an abundant lignocellulosic raw material in the mill region, corn stover, is converted to ethanol using a biochemical process: co-current dilute acid pre-hydrolysis and enzymatic hydrolysis followed by fermentation and ethanol purification. Process design capacity is 25 million gallons per year (MMGPY).
- Fischer-Tropsch liquids (FTL) – Lignocellulosic feedstock, forest-based woody biomass, is utilized in a thermo-chemical process for manufacturing a hydrocarbon mixture: dried and ground biomass is converted to synthesis gas using steam reforming, followed by gas clean-up and Fischer Tropsch (FT) synthesis. This process design also offers potential for production flexibility: synthesis gas can be used also as boiler fuel to generate steam and electricity instead of, or in addition to, FTL. FTL production design capacity is 12 MMGPY.

Key assumptions influencing allocation and assignment rates are given in Table 1. Based on these assumptions the system boundaries in the case study context are established (Figure 3). Because the retrofit projects modify only pulp mill processes (mass and energy integration between pulp mill and new processes), in the process simulation model the paper mill is modelled as simple source/sink of resources. On the other hand, some non-unit-level resource consumption (mainly Selling, General and Administrative (SG&A) resources) also impacts the paper mill's cost structure. Therefore the cost models also include the paper mill as one aggregate activity with unit and non-unit-level drivers, and thus cost impacts of a retrofit project on the paper mill are also considered.

Assumption	**Impact**
Retrofit project scope – process integration into pulp mill only	No process implications at the paper mill → no resource or unit-level driver changes due to retrofit at the paper mill
Minimum additional labour	Pulp mill labour drivers will change: based on suitable job description or position and availability, the headcounts of pulp mill departments are modified
Retrofit project goal – no changes in overall business unit and corporate overhead costs	Overhead costs (unit-level and non-unit-level) that are allocated based on headcount automatically considered. Other allocation bases updated accordingly (e.g. sales costs based on sales volumes)
Utility cost allocation approaches in P&P industry joint utilities constant pulp mill utility costs *	Changes in utility costs are absorbed by the paper mill and biorefinery, this includes both changed costs and revenues Modifications in asset and therefore changed fixed costs are assigned to all consumers based on allocation rates

* **Pulp mills are often energy self-sufficient because of the energy available from the pulping liquor. This is assumed to be a valid assumption for the retrofitted mill and therefore the utility costs are not expected to change. The utility cost for the pulp mill is based on the fuel mix available in the base case.**

Table 1. Key assumptions and their impacts on cost allocation and assignment drivers

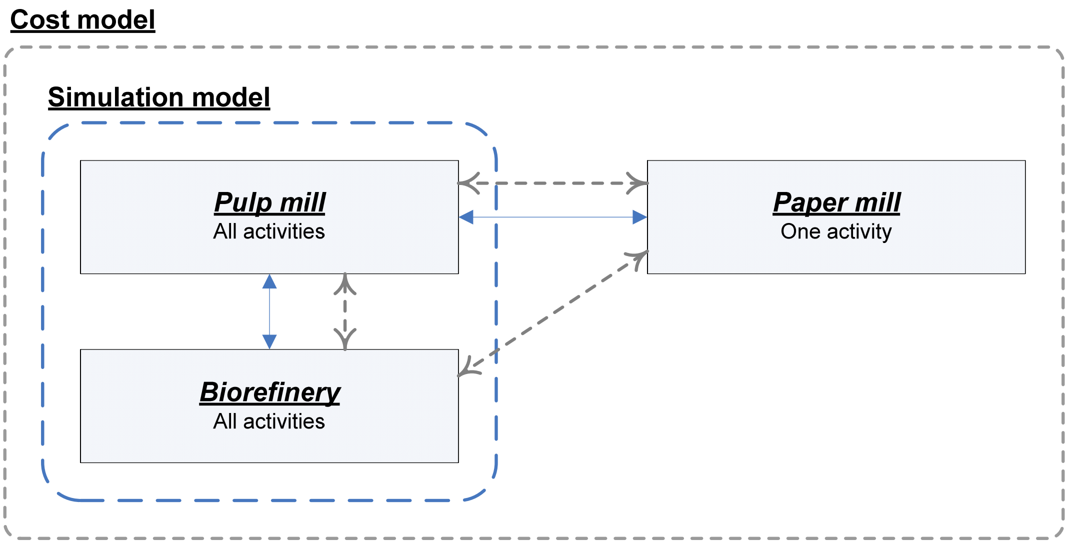

Figure 3. Structure of the modelling framework in the case study. Solid blue lines denote flow of material and energy, dashed grey lines flow of costs.

5 *Results and discussion*

5.1 Production costs and retrofit cost impact quantification

Pulp production cost competitiveness and the production costs of biofuels are shown in Figure 4 and Figure 5. The influence of the utility cost allocation method is illustrated in the biofuel production scenarios.

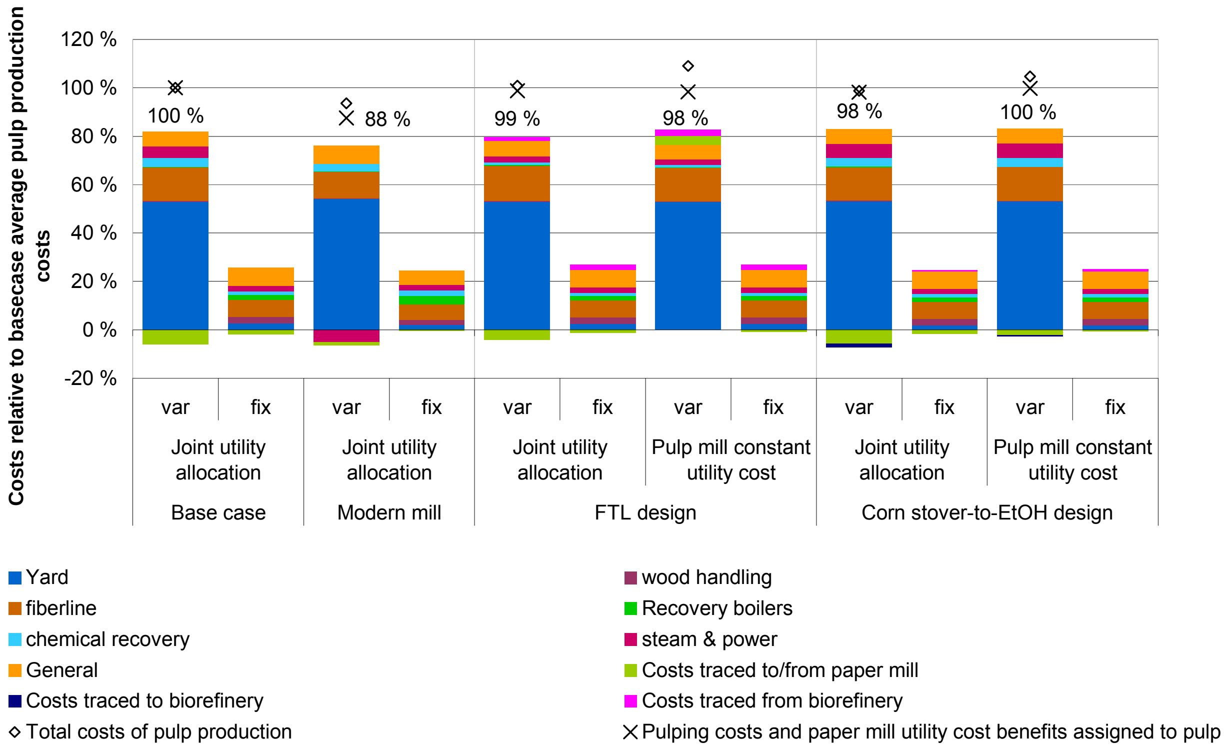

Figure 4. Relative pulp production costs (diamond denotes total costs and coloured bars the costs by mill area) and costs traced outside pulp mill in considered retrofit scenarios; impact of utility cost allocation method on pulp production costs and overall on pulp and paper production costs in biorefinery retrofit project scenarios (in base case and modernized mill scenarios only joint utility cost allocation method is reasonable).

Pulp production costs (diamonds) are significantly changed in all design scenarios. When the impact on overall pulp and paper production costs is assigned to pulp production costs (crosses), a relatively smaller change is observed for the biorefinery retrofit projects. On the other hand, traditional pulp mill modernization is able to substantially decrease pulp production costs even though pulp wood cost increases because the capacity is increased. In the FTL case, additional costs are traced to pulp from the FTL process (by-product steam and tail-gas – pink bar) whereas in the ethanol case the net cost transfer is from pulp to ethanol (steam cost – dark blue bar). The cost benefit realized at the paper mill due to the changed utility cost can be seen as difference in cost transfer to/from paper mill between base case and other cases (sea green bar). The mill modernization project improves significantly energy efficiency and this can be seen as 1) excess electricity production and therefore negative costs in steam & power department (lila bar), and 2) as lower steam costs that are seen as lower other department energy costs.

A different allocation basis also impacts the pulping costs. This is mainly due to the fact that biorefinery implementation significantly changes the energy costs (steam demand and therefore fuel mix and electricity production potential). Therefore, if it is assumed that the pulp mill has constant energy costs, other products will absorb these changes in energy costs.

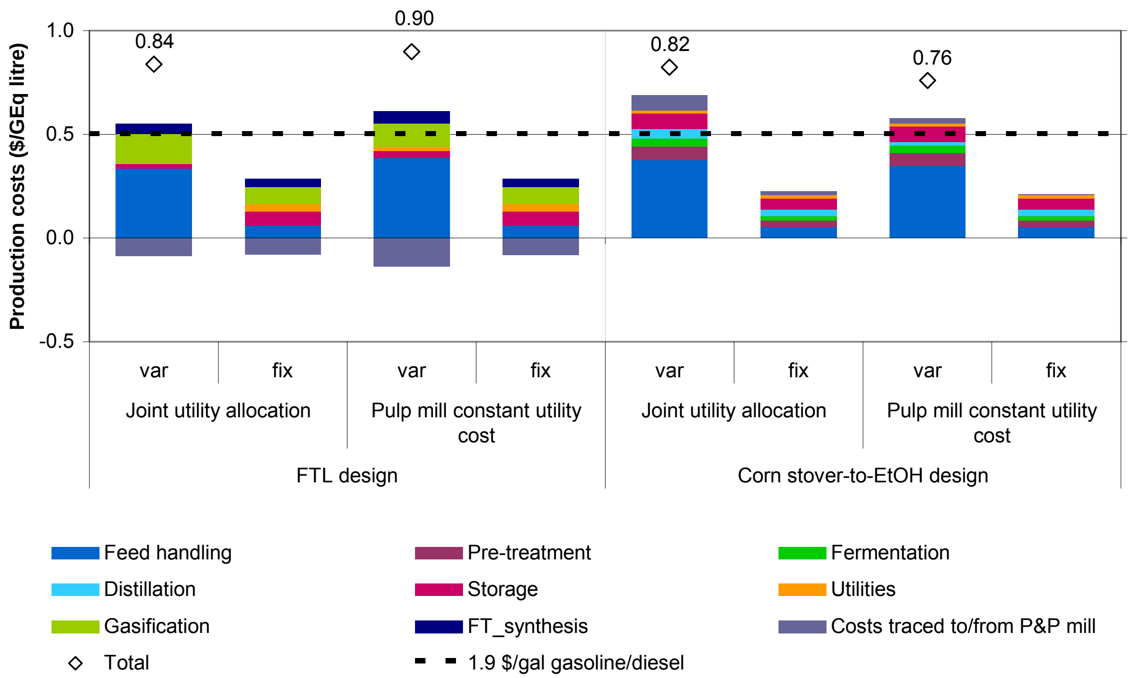

Figure 5. Biofuel variable and fixed production costs by plant area and costs traced between pulp mill and biorefinery shown as stacked columns and total biofuel production costs shown as diamonds in $ per gasoline equivalent litre of biofuel.

The biofuel total production costs (diamonds) show an opposite direction in the impact of the allocation method compared to pulp production costs (Figure 5). Neither of the biofuel alternatives is able to break-even alone, however a positive P&P mill cost competitiveness change can potentially generate a positive overall performance change. Feed handling is in both cases a major cost contributor (raw material costs are assigned to this department). The biggest difference between the two design alternatives is in the cost transfer between pulp mill and biorefinery: in the FTL case, costs are traced from biorefinery to pulp mill whereas in the ethanol case, costs are traced from pulp mill to biorefinery.

Figure 6 shows a more detailed view of the fixed costs by cost pools.

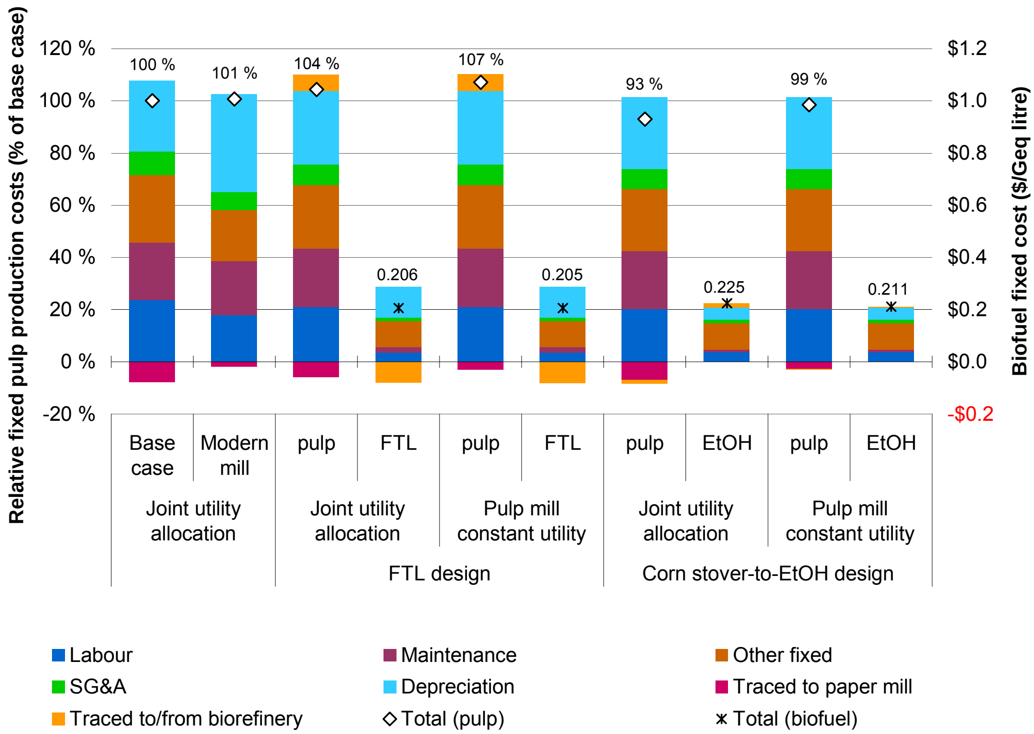

Figure 6. Relative fixed costs of pulp production and fixed costs of biofuel production. The fixed costs of pulp production (all high stacked columns) are shown on the left y-axis as percentage of base case fixed costs, and biofuel fixed production costs as $ per gasoline equivalent litre of fuel on the right y-axis.

Increased fixed costs of pulping are obtained in mill modernization and in the FTL case, but a significant decrease can be observed in the ethanol case. Differences can be seen mainly in depreciation costs (mill modernization project investment is fully assigned to the pulp mill) and labour costs as was expected based on the study assumption. Also depending on the biorefinery scenario, fixed costs can be traced either to or from the biorefinery to the pulp departments due to the assignment of intermediate resources based on consumption (it is assumed that both variable and fixed costs are assigned using the same driver). This also is the reason why between different allocation schemes the fixed cost transfer between pulp and biorefinery departments changes (other fixed costs are constant as should be the case).

As can be observed from the fixed cost changes, without a systematic and detailed operations-driven cost analysis method, these significant cost impacts would be missed in design analysis.

The allocation method has no influence on total cash flow of the facility, however the cost impact can be seen in different product costs. For example, constant pulp mill energy costs show lower variable costs of pulp production for FTL scenario but at the same time the fixed costs are higher than when energy costs are allocated using joint allocation method. At the same time, FTL variable costs are higher and fixed costs lower than when allocated using joint allocation method. Thus, different cost allocation practices can potentially lead to a penalizing effect or overestimation in product costing. Important is also to note that even a cost change of one percentage in the P&P industry can significantly change the cost position of a producer.

In both the pulp and biofuel production, energy cost are in a key role. Figure 7 demonstrates how steam costs are changed under different steam demand and supply, and fuel-mix conditions resulting from different retrofit design scenarios shown in Figure 8. Even though the steams and by-product solid waste are only intermediates, their price (production cost) is explicitly defined in the intermediate resource cost table (in $/unit). The cost calculations are based on actual steam turbines at the mill with fixed steam loads (e.g. described by Smith and Varbanov (2005)). The steam network of all retrofit design scenarios has been optimized in process simulation in order to calculate the steam production cost (objective: maximum electricity production; decision variables: turbine VHP steam flows, boiler fuel flows; constraints: boiler steam flow and fuel loads, turbine section flows, condenser flow, steam headers in overflow).

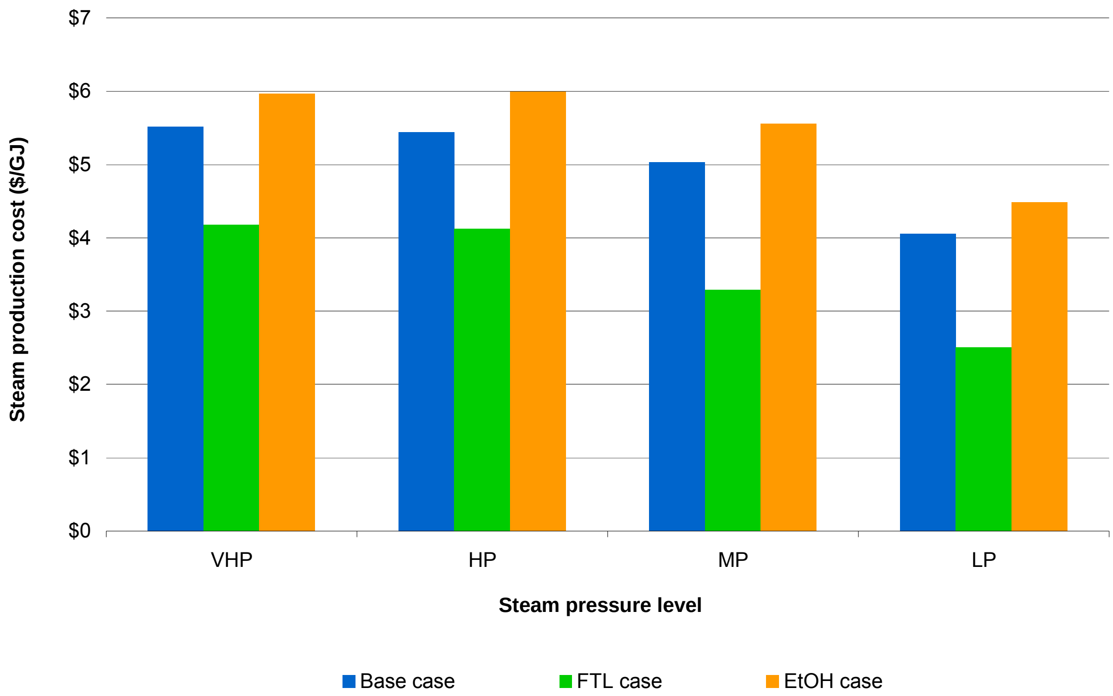

Figure 7. Average steam production costs ($/GJ) in considered scenarios; fossil fuel prices fixed to mill costs, process residue (bark, black liquor, biorefinery solid residues and syngas) costs calculated; VHP – very high pressure, HP – high pressure, MP – medium pressure and LP – low pressure

The average cost of steam at all pressure levels is the highest in the corn stover-to-ethanol scenario and lowest in the FTL scenario. This can be explained by the different fuel-mixes and turbine utilisation rates as is illustrated in Figure 8.

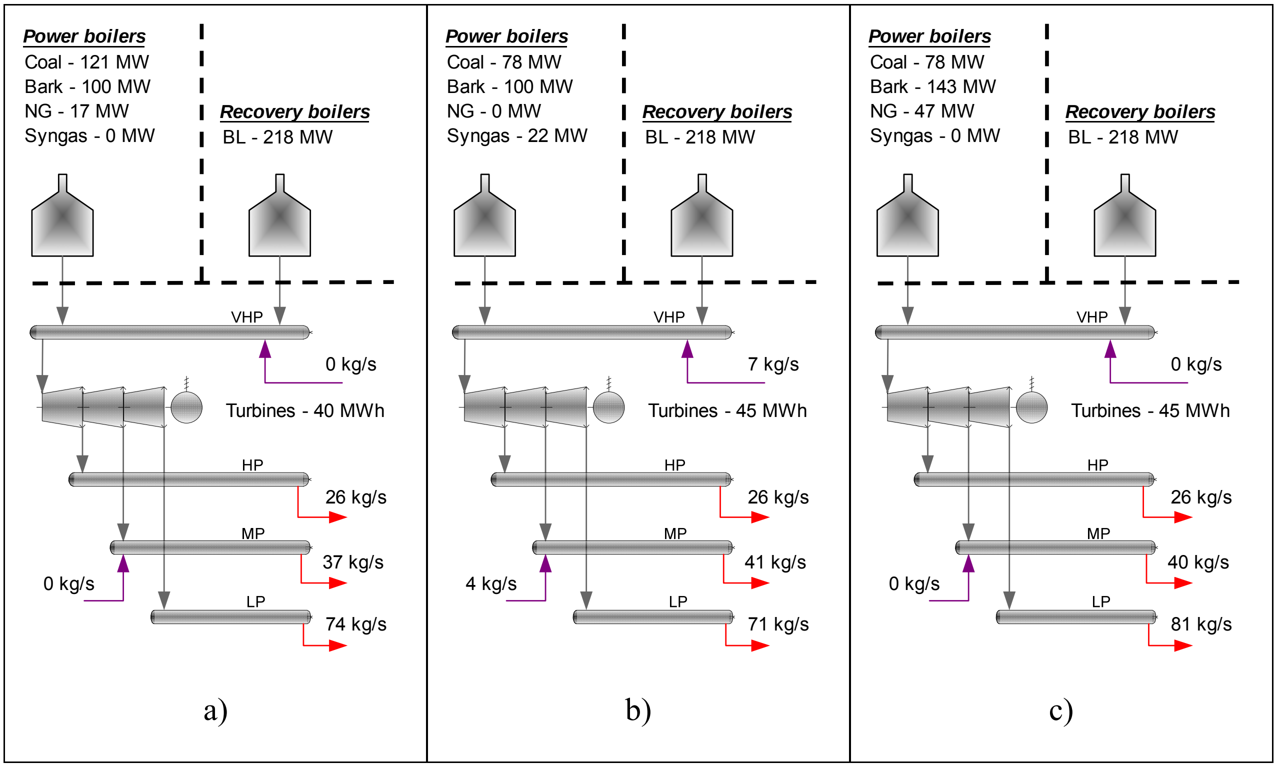

Figure 8. Steam and power system in a) base case, b) FTL case, and c) corn stover-to-ethanol case. Red lines denote process steam demand and violet by-product steam produced in the FTL process. The dashed lines illustrates the division of steam and power production into recovery boiler, power boiler and turbine departments for operations-driven cost model.

Electricity production is maximized while constraining the vented low pressure (LP) steam amount to the condenser capacity. This leads to full utilisation of process residues (bark, biorefinery solid residues and tail-gas) and the use of the lowest cost fossil fuel (coal). Only in case of higher steam demand than can be supplied with these fuels natural gas is used. Different electricity production rates between design scenarios are the result of different medium pressure (MP) and LP steam demand and system constraints: process steam is bled from the turbines and the turbine section capacities constrain the electricity production under changed demand even if the turbines are not run at maximum capacity. The results are of course case specific: depending on the costs of different fuels, the price of electricity at the mill and system constraints of the mill, another optimal fuel mix and electricity production rate would result.

It is clear that without operations-driven costing -based production cost estimates showing how the costs will look like when the process is implemented and accounting is reporting the costs, the product costs would be distorted. This can potentially give wrong impression of the overall goodness of the capital spending scenario, for example the case study shows decreasing production costs of pulp which might not be the case for all scenarios.

5.2 Marginal cost analysis

Pulp and paper producers can have a significantly changing order book and many contracts. Therefore transactions occur at different prices and potential for high marginal prices is relatively high. Marginal cost information is therefore important to decide at which production capacity this margin is optimal. When making capital investment decisions, this information also gives an indication of how dynamic the retrofitted process is with regards to changes in P&P markets. Biofuels may be sold more often under contracts that cover a longer time period and the marginal price is therefore not an everyday question. This can be further highlighted by the low production capacity of future lignocellulosic biofuels in integrated forest biorefineries (low cost production requires often small capacity because of high raw material costs): fuels are most likely sold to only one fuel distributor at a time, compared to several buyers of pulp and paper products.

In addition to strategic modifications of the facility, mills execute many improvement programs in order to stay cost competitive: energy improvement programs to achieve better energy efficiency (lower primary energy consumption per unit of production), mill productivity improvement programs to produce more, thus increasing department level and mill production uptimes, environmental programs to enhance the environmental footprint of the products, and labour productivity programs to produce more product per man hour. These programs are normally several year-long strategies. Especially energy efficiency programs rely on evaluation of the marginal cost of steam as a basis for identification of the most expensive steam for the facility and projects to lower the cost of that steam. When a new process is heat-integrated into the mill, the demand of steam and therefore the cost of steam will change as was seen in Figure 7. This in turn can change the marginal cost of steam and planned improvement projects might become obsolete, impossible or their impact and payback time becomes less favourable.

Figure 9 shows the marginal and average cost of P&P production in the base case and two biorefinery cases, and the average cost of BR product production. Marginal costs are calculated using equation 1. Figure 10 illustrates the product profit margins and total margin of the plant.

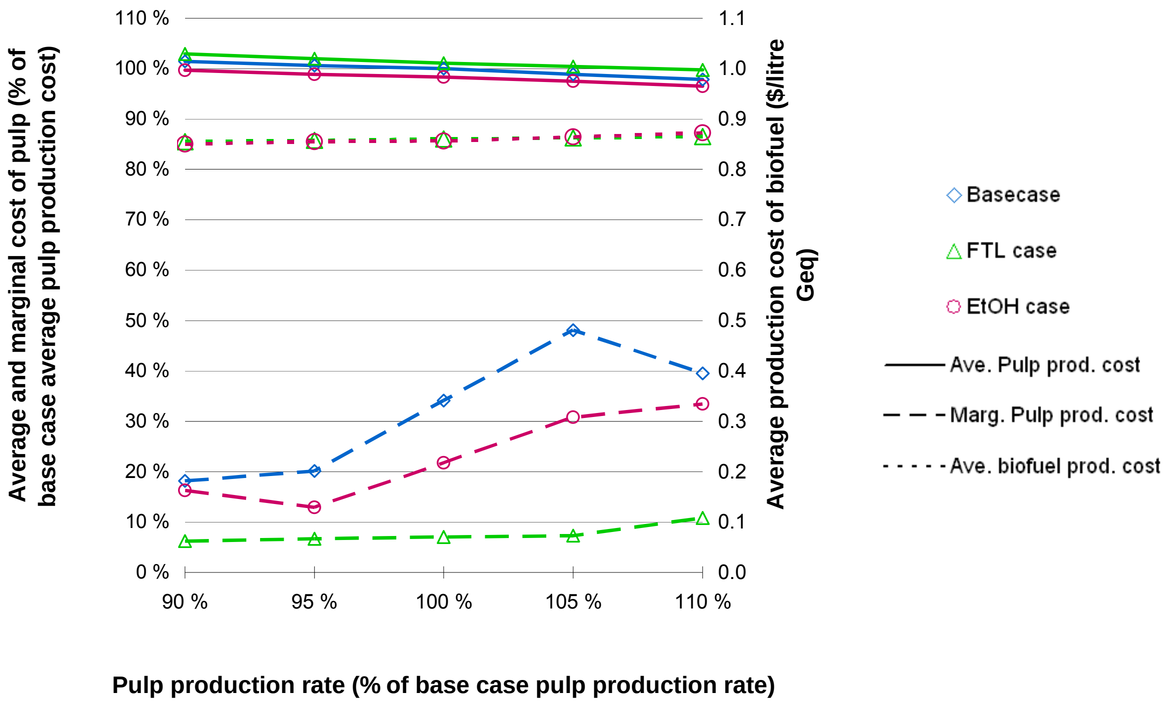

Figure 9. Average and marginal cost of pulp and average cost of biofuel as a function of pulp production rate. Pulp production costs shown as percentage of base case costs, biofuel production costs as $ per gasoline equivalent litre of biofuel

Average pulping costs (denoted with solid lines) decrease in all scenarios when the pulp production rate increases. This kind of economy-of-scale behaviour is common for large-scale manufacturing such as pulp and paper production.

The marginal production cost of pulp (dashed lines) is significantly lower than the average cost of pulp and increases when more pulp is produced. In the base case and corn stover-to-ethanol case the marginal cost of pulp first increases faster than in the FTL case. This results from the energy system utilisation and constraints: the mill uses coal and natural gas as additional fuels to supply steam to the processes. The hog and coal boilers are used at their maximum capacity with 100% production rate and when the pulp production rate is increased, more bark is also generated. To be able to burn all bark, the coal feed to the boilers is decreased in order not to exceed the boiler maximum fuel load. This also leads to a lower heating value of the fuel mix in those boilers (the heating value of coal is higher than the heating value of bark). Process steam demand is therefore met using natural gas. The electricity production rate is constrained by the turbine section flows at lower pulp production rates. At higher production rates more turbine capacity can be utilized because the relative bleed steam demands approach the turbine design specifications. In the FTL case, marginal pulp production cost increases slowly with increasing pulp production rate.

Average biofuel production cost is not significantly impacted when pulp production rate is changed. The slight increase results from increased utility costs.

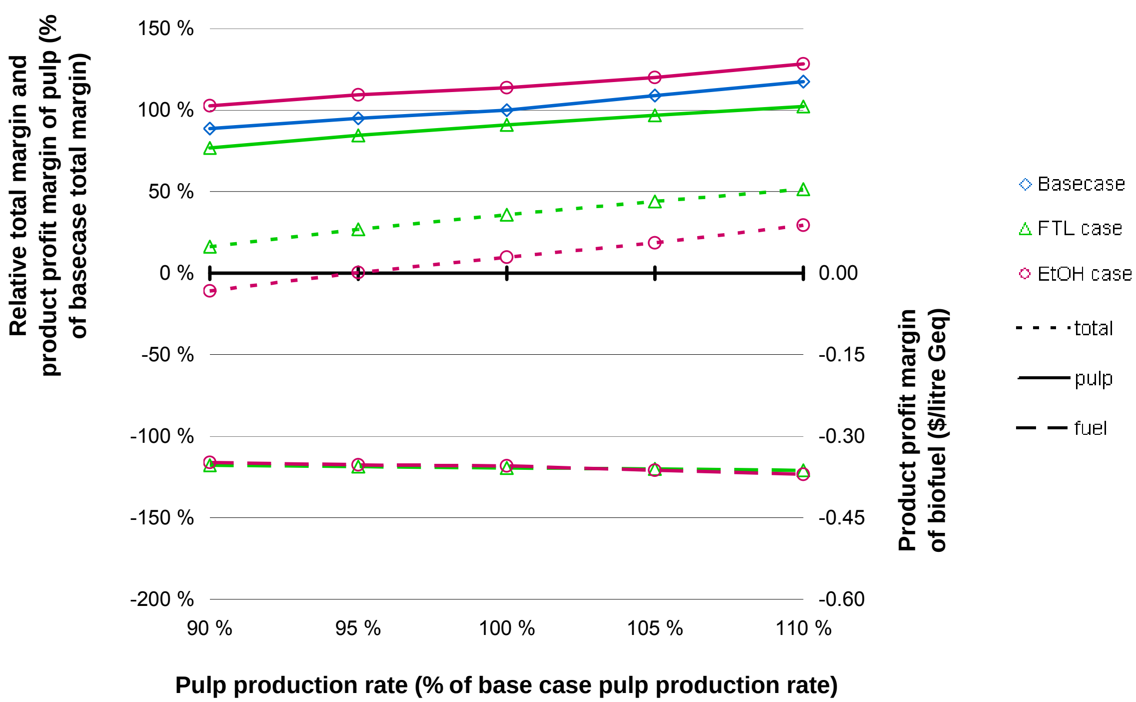

Figure 10. Product profit margins and total margin as a function of pulp production rate

Figure 10 demonstrates the combined impact of pulp production cost changes and the production cost of biofuel, shown in Figure 4 and Figure 5, on the margins: the base case total margin (solid blue line) is significantly better than the margin of biofuels producing FBRs (dotted lines). From the biorefinery designs, the FTL production performs overall better (combined margin) even though the pulp product profit margin in this case is much lower than in the corn stover-to-ethanol case. Biofuel product profit margins are positive for FTL and highly negative for ethanol (EtOH) case.

One major contributor to these differences is energy cost: From Figure 7 and Figure 8 the steam cost differences and the reasons for these differences are clear. The high steam cost in the EtOH case, and similarly the low cost in the FTL case, can be traced to the boiler fuel mix. In the EtOH case, lignin-rich solid residues from the biorefinery replaces coal in boilers because the boilers are used already at their maximum fuel load levels and all bark needs to be burned. A lower heating value fuel mix generates less steam and the process steam demand is met by using natural gas. On the other hand, in the FTL case the integration of the bioprocess generated VHP and MP steam that can replace coal/natural gas -based steam, and tail-gas from the FT-synthesis (excess gas after lime kiln use) can be used in a natural gas boiler to generate additional steam and replace natural gas to lower steam costs.

Multi-fuel-based combined heat and power production (in addition to process wastes such as bark, black liquor and waste water treatment sludges, pulp mills burn fossil fuels to supply steam and power) enables process flexibility in terms of electricity production and fuel mix if these fuels have other possible uses. Biorefinery processes often bring a new fuel into the system, in case of the FTL process this fuel could be synthesis gas (syngas) which can be used either to generate steam and power utilising existing a natural gas boiler and turbines, or to produce FT-liquids. In Figure 11, the average P&P and FTL production costs are illustrated as a function of FT-synthesis rate and resulting electricity production rate. Here it is assumed that the installed new processes (FTL process and additional condensing steam turbine) with existing systems possess full flexibility in diverting the syngas from FT-synthesis to a natural gas boiler.

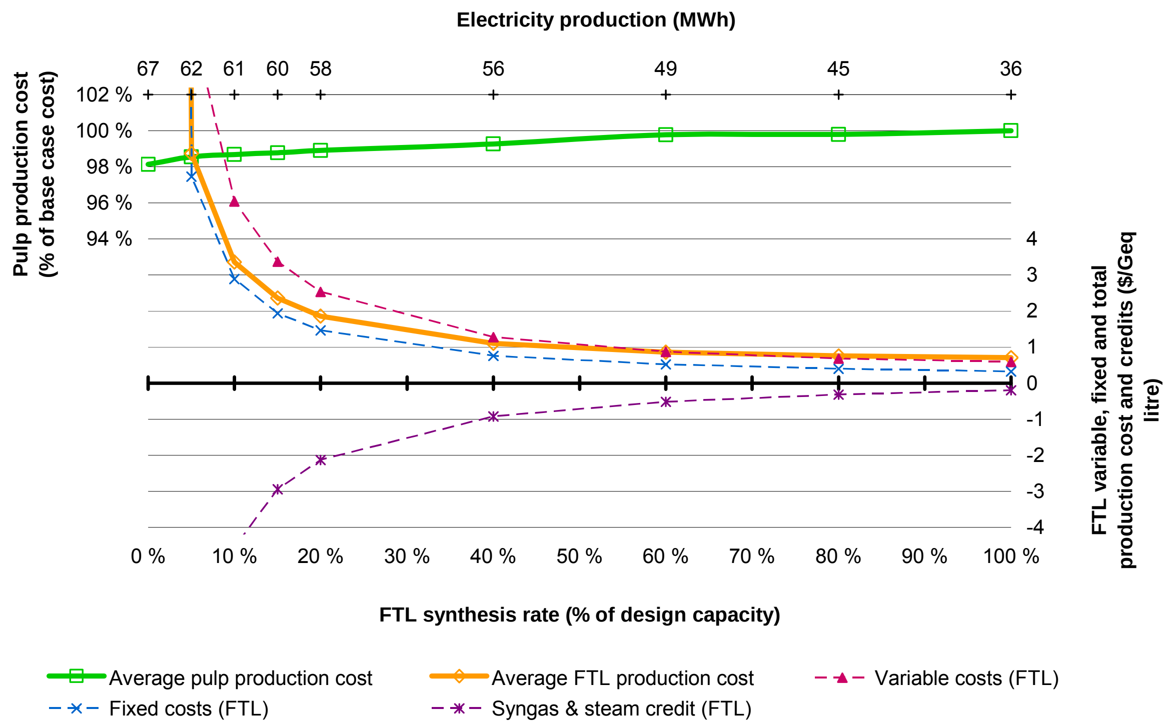

Figure 11. Average production costs of pulp and average, variable and fixed costs and credits from by-products (syngas, tail-gas, steam) of FT-liquids production with FT-synthesis flexibility. Syngas production is constant, excess syngas (after FT-synthesis) is utilized in steam and electricity production.

FTL production costs are composed of variable costs (triangles), fixed costs (crosses) and credits from synthesis gas and steam (stars) that all decrease as the FT-synthesis rate increase.

The design capacity is the lowest cost FTL production capacity. Pulp production costs at this lowest-cost FTL production rate are higher than at other production rates. These costs are a result of the utilization of the flexible production system: when more FT-liquids are synthesized, less electricity can be generated and both the pulp mill and FTL process have higher energy costs. Thus, electricity price can impact the production costs.

When the production costs are translated to product profit margins and total margins, the most promising production rate at the used electricity price can be obtained. This is illustrated in Figure 12 with aggregated contribution margin calculated using equation 2.

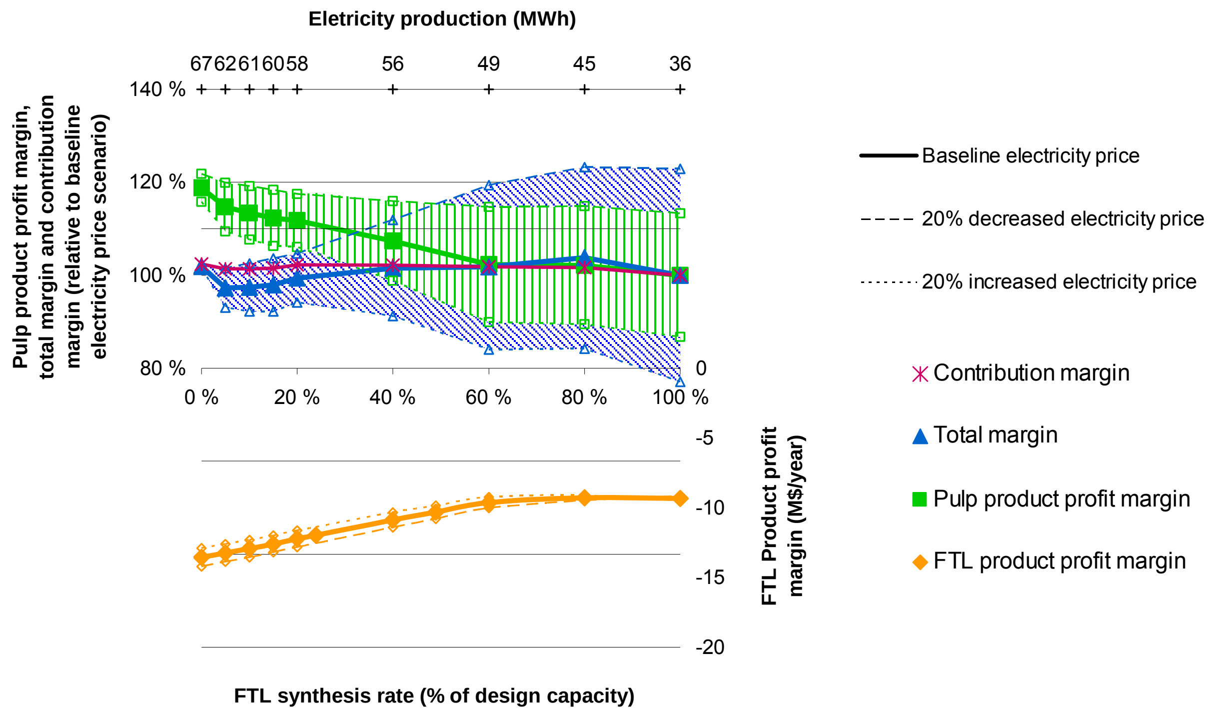

Figure 12. Product profit margins of pulp and FT-liquids, total margins (assigned to pulp) and total contribution margin with FT-synthesis flexibility.

Individual product profit margins of pulp and FTL would indicate opposite production rate selection: from a pulp product profit margin viewpoint, no FT-liquids should be produced, whereas if the FTL product profit margin is considered, 80% - 100% synthesis rate of FT-liquids from the design capacity should be selected. The highest total margin is however the scenario when the entire FBR is most profitable and this is found at 80% FTL process design capacity. This is also the capacity at which the contribution margin is at a maximum with baseline electricity price, meaning that all products are contributing the highest leverage to pay off fixed costs.

Different electricity prices would change both FT-liquids and pulp production costs. In Figure 12, impacts of 20% increase and 20% decrease in electricity price are shown with dotted and dashed lines, respectively. Counter intuitively, higher electricity price will not enhance the performance of this design: the electricity demand of the FBR is higher than can be produced if no additional natural gas is purchased (assumption was not to purchase fossil fuels) up to the point when about 40% of syngas is synthesized to FT-liquids (about 56 MW). Therefore, a lower electricity price is beneficial for the design especially when more than 40% of the syngas is synthesized to FT-liquids.

6 Implications for capital appropriation

Systematic interaction between accounting and engineering in strategic capital investment project analysis process is critical in two ways: 1) it can significantly enhance the reliability of the engineering process design analysis by introducing appropriate indirect cost charges, and 2) it enhances communication of the process impacts of strategic investments to decision makers by using standard reporting tools (different financial statements) as process reports. Thus, decisions can be made based on more accurate measures using well-known and understood metrics.

When the future trends of prices and improvement programs are represented in the analysis framework as resource and activity driver trends, reliability of the investment scenario results can be further enhanced. For example, implementing planned future annual plant efficiency improvements (labour productivity, reliability or uptime, energy efficiency) as process-level changes in the process model and/or cost driver trends in the cost model, enhances near-term cost forecasting in the model.

Another important feature is systematic risk analysis. Uncertainties in future market trends (management and marketing knowledge) and process level impacts of process modifications and future reliability (process engineering knowledge) are systematically and fairly assessed for all strategies in question and can be used in many types of risk analyses. For example, project- or facility-level performance can be assessed under specified fixed future business environment scenarios or using stochastic descriptions of a business environment. The combination of ABC and Monte-Carlo analysis was described in general by Emblemsvåg (2003). It was also illustrated by Hytönen et al. (2010) in the same case study context used in this study: retrofit projects were analysed under external uncertainties (prices and price trends of products and feedstocks, capital investment cost) using the methodology proposed in this study. Monte-Carlo simulation was used. The measure of risk was worst-case scenario project profitability – expected profitability value less two times standard deviation (internal rate-of-return and net present value). In addition, process–based uncertainties (such as labour intensity, process yield, energy intensity) can easily be implemented in the proposed costing method because these uncertain parameters are explicit drivers of cost model or process model parameters.

This study used one steady-state operating regime to describe the production scheme of the facility. The P&P processes operate in different steady-states (and transient states) during a longer time period. This multi-state behaviour of the production system can be modelled with the approach presented here: process knowledge and data analysis of the existing process and understanding of the new retrofitted processes can be used to identify and quantify the possible steady-state conditions and their probability of occurrence. These identified conditions are supplemented with the process model to obtain all resource and activity drivers for each regime. Then the investment project analysis can be conducted as an aggregation of multiple steady-states using the operations-driven costing method proposed here instead of developing dynamic models.

With low-margin products (such as all studied commodity products in the case study presented) reacting to the changing business environment is not only a short-term issue but also a strategic choice. By analysing the potential of an investment alternative to proactively react to foreseen possible changes can significantly improve the long-term performance of the facility and the company, and emphasize the potential of that investment alternative. This can be achieved by utilising an operations-driven costing framework such as proposed here to analyse the marginal performance of the system. For instance, steam cost analysis and identification of energy projects under changes in fossil fuel and wood prices can be done to evaluate the future continuous improvement program costs of different investment scenarios. This can potentially show significantly different potential for different investment scenarios. Alternatively, under possible end-product price trends, the impact of running the system with lower/higher capacity utilisation rate can be assessed. This can also be used to estimate future needs for drastic product price changes and potential product add/drop decisions and their impacts on project performance.

7 Conclusions

Techniques for obtaining reliable product costs after retrofit projects for management decision making have not been proposed in the literature. A method for retrofit project manufacturing cost analysis using operations-driven costing (based on activity-based costing principles) linked with process simulation was presented and demonstrated. A case study of retrofit implementation of the forest biorefinery at a kraft pulp and paper mill was considered. Both of the tools that are linked in the proposed costing method are separately used in continuous industries for every-day process analyses and accounting purposes. Thus, when linked they should provide excellent cost estimation and integration cost impact evaluation accuracy compared to normally conducted, simple cost calculations of retrofit projects. Importance of accuracy in operating cost impact estimation of retrofit projects is emphasized by the P&P industry dynamics: increasing costs of energy and raw materials and decreasing end-product prices of an already low-margin industry make it imperative to accurately estimate the impacts of facility modification and all future product costs (including the current products) for finding best strategic decision making.

The method was applied to three retrofit design scenarios, one traditional pulp mill modernization project and two biorefinery implementation projects. Impacts on pulp production costs and biofuel production costs were examined using two different cost allocation practices. Production cost–wise, the traditional mill modernization project has the highest potential to enhance cost competitiveness of the facility, whereas the biorefinery projects have a relatively smaller impact on pulp production costs. The cost allocation method influences the individual products' production costs and can potentially overstate or understate the true cost of production and it is therefore an important factor to understand the implications of selected allocation practise in retrofit cost analysis.

In the case study, FT-liquids production from woody material seems to have somewhat lower production costs than ethanol production from corn stover; this stayed unchanged with both tested allocation practises.

Additional feature of the proposed method is its capability to calculate marginal costs and product costs when some production variable is changed (e.g. production rate). Marginal costs and product profit margins were demonstrated in both biorefinery scenarios, and production costs with flexibility in FT-synthesis rate in the FTL design scenario. The marginal production cost of pulp is relatively much higher in the base case and ethanol case compared to the FTL case. It also has different behaviour resulting from the utilization of the steam and power generation system. Production costs at different production rates of FT-synthesis can be used to estimate the trade-offs between producing the different products (FT-liquids and electricity) and to evaluate the value of a flexible investment strategy. In the case of FTL production vs. syngas production for steam and power production, the total margin (with used price of electricity) indicates that all synthesis gas should be synthesized into FT-liquids.

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Abbreviations

ABC – Activity based costing
adt – air dry ton (moisture content 10%)
bdt – bone dry ton (moisture content 0%)
C – cost
CM – contribution margin
dep – department
depr – depreciation
EtOH – ethanol
FBC – functional-based costing
FBR – forest biorefinery
FC – fixed costs
FSC – full standard cost
FT – Fischer-Tropsch
FTL – Fischer-Tropsch liquids
HP – high pressure (steam)
i, j, k, m, n – indices defined in corresponding context
LCC – life-cycle costing

LP – low pressure (steam)

MC – marginal cost

MCDM – multi-criteria decision making

MMGPY – million gallon per year

MP – medium pressure (steam)

M&E – mass and energy

NG – natural gas

NPV – net present value

pdf – probability density function

P – price

P&P – pulp and paper

Prate – production rate

R – revenue

SG&A – sales general and administrative expenses

Syngas – synthesis gas

TC – total costs

VC – variable costs

VHP – very high pressure (steam)

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APPENDIX D – Article: Design methodology for strategic retrofit biorefinery capital appropriation

Design methodology for strategic retrofit biorefinery capital appropriation

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Abstract

This paper presents a methodology for enhancing the strategic investment decision making process for retrofit forest biorefinery implementation. This is achieved by improving the link between retrofit process design and capital appropriation activities through cost accounting. This novel methodology is based on step-wise screening of retrofit alternatives. Traditional techno-economic analysis and multivariate stochastic risk analysis are used in the first pre-screening step. An advanced analysis framework based on steady-state process modelling, product costing using principles of activity-based costing (ABC), and panel-based multi-criteria decision making (MCDM) is used in the second selection step. In the MCDM, financial and risk -based decision making criteria are used. The methodology is demonstrated using a case study considering retrofit biorefinery implementation into a kraft P&P mill.

Application: This work highlights the potential of existing process and cost analysis capabilities, and group decision making methods in strategic investment decision making related to retrofit forest biorefinery implementation, emphasizing systematic incorporation of uncertainties in the decision making.

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Introduction

Forest biorefinery (FBR) is an environmentally benign approach for supplying part of the energy, chemicals and materials demand of the society. It is also increasingly been considered as potential future business for traditional forest industry. FBR is partly based on the same principles, and it targets the same market sector, as traditional petro-chemical industry. However, forest industry possesses an advantage over the chemical industry that is the long experience in bio-based feedstocks and their processing. The current pulp and paper (P&P) industry's competitiveness in traditional P&P countries makes however the investment decision making challenging. This results from the ageing assets, high energy costs and strict regulations. Moreover, the pressure on the design and decision making processes in identifying the right opportunities is increased.

Identification and management of the characteristics and uncertainties of the process technologies and the new FBR business is required for the strategic investment decision (SID) making. Currently, many methods are applied in different functions of the business life-cycle to analyze similar characteristics and impacts of uncertainties. At process level, retrofit and greenfield process design methods and tools are applied to investigate project feasibility and profitability for potential operational and strategic projects; at business or facility level, advanced cost accounting methods are used to analyze manufacturing system cost-performance, financial reporting is conducted to report business performance periodically, and group decision making is utilized in strategic planning and investment decision making.

Retrofit process design for forest biorefinery

Various FBR process strategies and designs have been proposed. Traditionally the biorefinery processes are categorized into biochemical and thermo-chemical pathway processes. For integrated forest biorefinery, the division into adjacent and tightly integrated biorefineries based on the level of integration is more useful: adjacent processes only utilize the existing systems but do not interfere with the pulp and papermaking material balances, whereas tightly integrated biorefinery processes are also exchanging energy and material with the P&P processes. Examples of tightly integrated FBRs include extraction of hemicelluloses prior-to-pulping for ethanol and bio-chemicals production using green liquor [1-3], hot-water [4, 5], or partial dilute-acid prehydrolysis [6], black liquor gasification combined cycle system for Tomlinson recovery boiler replacement and simultaneously biofuels production [7, 8], or carbon dioxide and sulfuric acid utilization for lignin precipitation and filtration from black liquor [9]. Possible adjacent strategies include for example thermochemical treatment of bark or forest biomass using steam-reforming [10] or high temperature gasification [7, 8] followed by Fischer-Tropsch liquids (FTL) or mixed alcohols synthesis, or first-generation biofuels production from corn [11, 12].

Many of the literature FBR studies are concept demonstration or pre-feasibility level analyses of only one technology (Figure 1).

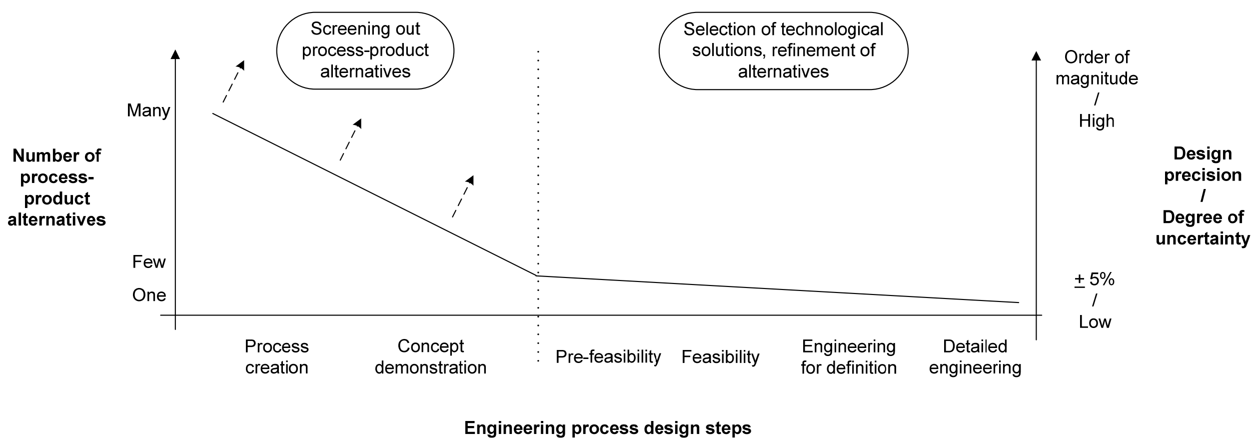

Figure 1. Engineering process design steps and their main functions

Several overall retrofit process design methodologies have been proposed, mainly focusing on the pre-feasibility stage process design. Janssen proposed a generic retrofit process design methodology comprising of process and supply chain level assessment steps, targeting more sustainable capital spending decision [13], Uerdingen, Fisher et al. demonstrated the use of a novel methodology for systematic identification, development and evaluation of retrofit design alternatives with and without capital investment using a case study in fine chemicals industry [14, 15], and process integration investment decision making under uncertainty was studied by Svensson et al., targeting especially energy efficiency improving strategies [16, 17]. However, methods specifically for FBR design have not been proposed.

Cost analysis in investment decision making and process design

The surveys of Farragher et al. [18] and Hogaboam and Shook [19] related to capital investment decision making practices imply that relatively detailed level operating costs evaluation is used to arrive at good forecasts of annual operating cash returns, changes in working capital and their residual cash flows. This product costing is done mainly using traditional volume-based costing, but also activity-based costing (ABC) (Figure 2) is applied [20]. ABC is considered more transparent and accurate costing method due to its capability to properly allocate overhead costs [21-23].

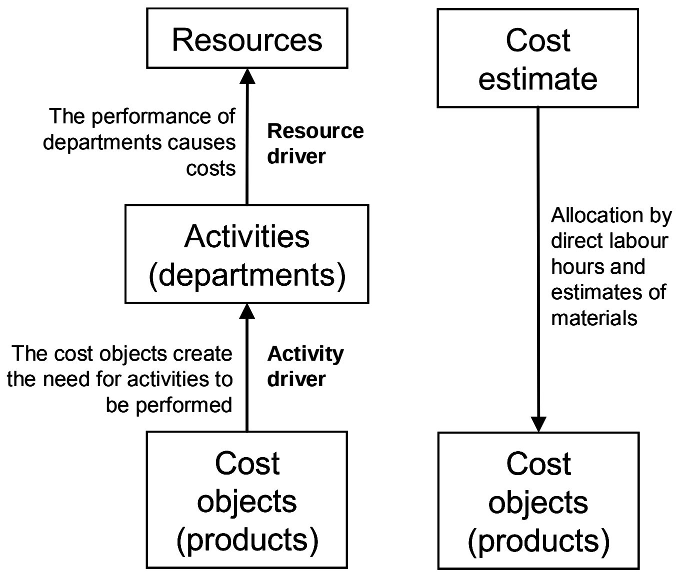

Figure 2. Differences between ABC and traditional cost accounting

The overhead cost allocation has gained increasing interest in the recent management accounting literature [24]. Major reasons for this are the need to be able to better respond to changes in market place and to optimize the manufacturing system for the chosen product mix. For example, proper overhead cost allocation can reveal the opportunity costs of alternative use of the fixed asset and can steer to optimized product mix (in oligopoly markets), and thus using full costs in decision making rather than variable costs only (marginal costs) gives a better market response [25].

Assignment of joint utility costs also impacts the design analysis. Moreover, the calculation of the utility costs, especially the key P&P industry utility cost (steam) can use several cost assignment bases (enthalpy or entropy difference, electricity generation potential, or exergy [26, 27]) and each results in different steam costs. Thus, retrofit implementation changing both the energy system and the joint utility consumption needs rigorous joint cost analysis.

Advanced cost analysis methods have been proposed for process design: Sadhukhan developed a process synthesis methodology for retrofit process design based on value analysis [28, 29], Janssen et al. introduced the utilization of ABC-like cost modelling in a single-product and multi-feedstock system retrofit design problem in mechanical P&P making context [30, 31], Varbanov, Perry et al. [32] and Smith and Varbanov [26] utilize marginal cost analysis in a top-level analysis methodology developed by Makwana et al. [33] calculating the true cost of utilities using joint cost assignment rule, and Sandström investigated the fit between management costing and engineering design, focusing on how the ABC system should be constructed to be used in product costing in process design [34, 35]. These methodologies have however not exploited the full potential of advanced costing (multi-product costing) that is important for retrofit FBR decision making.

Risk analysis

In process design, several sources of uncertainty exist (model-inherent, process-inherent, external and discrete based on their nature [36]). Most commonly external uncertainties are considered with the aim at capturing the uncertainties at the outset of the design project, namely the uncertainties at company, industry or general environment levels [37]. The importance of risk analysis in retrofit FBR design project evaluation is clear when considering the case when no risk assessment would be conducted: “implicit assumption is that all projects considered are of equal risk and that risk is the same as the risk for firm as a whole” [38].

Qualitative and quantitative methods can be used for incorporating uncertainty into the techno-economic design analysis. These include subjective methods such as SWOT-analysis (project Strengths, Weaknesses, Opportunities, and Threats –evaluation) and different scoring methods, deterministic methods such as scenario analysis and sensitivity analysis, and stochastic methods such as Monte-Carlo analysis. The survey of Hogaboam and Shook [19] indicate that in the forest industry sensitivity analysis and subjective adjustment of cash flows are the most commonly used risk assessment methods. For better screening and selection between uncertain FBR scenarios, more systematic methods accounting for probability of occurrence have not been proposed.

Strategic investment decision making

In strategic planning process, the mission and drivers such as global economy, environmental regulations or resource productivity influence the company strategy. Strategy is reflected to plans and realized through investment and other programs. The connection between a single capital investment project and the company strategy is thus considered to be one-directional [39-44]. The capital investment project appraisal generally follows a five step process: 1) Identification of potential investments; 2) Project definition and screening; 3) Analysis and acceptance; 4) Implementation; 5) Monitoring and post-audit [41, 42, 45, 46]. The same appraisal process is often applied to the main types of capital investment projects (infrastructure, strategic and operational).

Angelis and Lee proposed a methodology for utilizing ABC already adopted for accounting in a company as a costing method for evaluating cost-impacts of investment strategy on individual activities [47], Sawhney used activity-based modelling to evaluate the investments' performance related to manufacturing strategy components (e.g. capacity, productivity, lead time, quality) [48], and Emblemsvåg [49] or Rivero and Emblemsvåg [50] have used ABC to evaluate life-cycle costs of different long-range scenarios (budgeting scenarios) of a facility or a company. Thus, advanced costing for SID making has been studied, but not linked to process design activity.

The investigation by Hogaboam and Shook [19] on performance measure use in US forest industry capital budgeting and rationing concluded that corporate strategic factors, such as potential competitive advantage, or markets, are a key component in SID making, decisions are mainly made based on developed investment goals (strategic and financial), and that IRR and NPV are the main techniques used. This indicates that investment performance metrics used by investors and shareholder are not used in project evaluation: investors utilize financial statements from previous accounting periods as the basis and different techniques to capture the relevant viewpoint of their investment (capability to pay debt, operating or capital efficiency). Hence, the value of an investment opportunity to the investors is not used explicitly in capital budgeting.

Objectives

The objectives of this paper are:

- To elaborate a new methodology for strategic retrofit investment decision making that makes better use of existing process and cost analysis, and management accounting activities
- To demonstrate the use of this methodology for decision making that accounts for project performance and strategic fit, and thus, considers the preferences of many of the company stakeholders
- To apply this methodology to a case study of retrofit biorefinery implementation in a North-American hardwood kraft pulp and paper mill

Overall methodology

The overall methodology consists of four steps and two decision making gates. The methodology is illustrated in Figure 3 and the main steps are elaborated in following sub-sections.

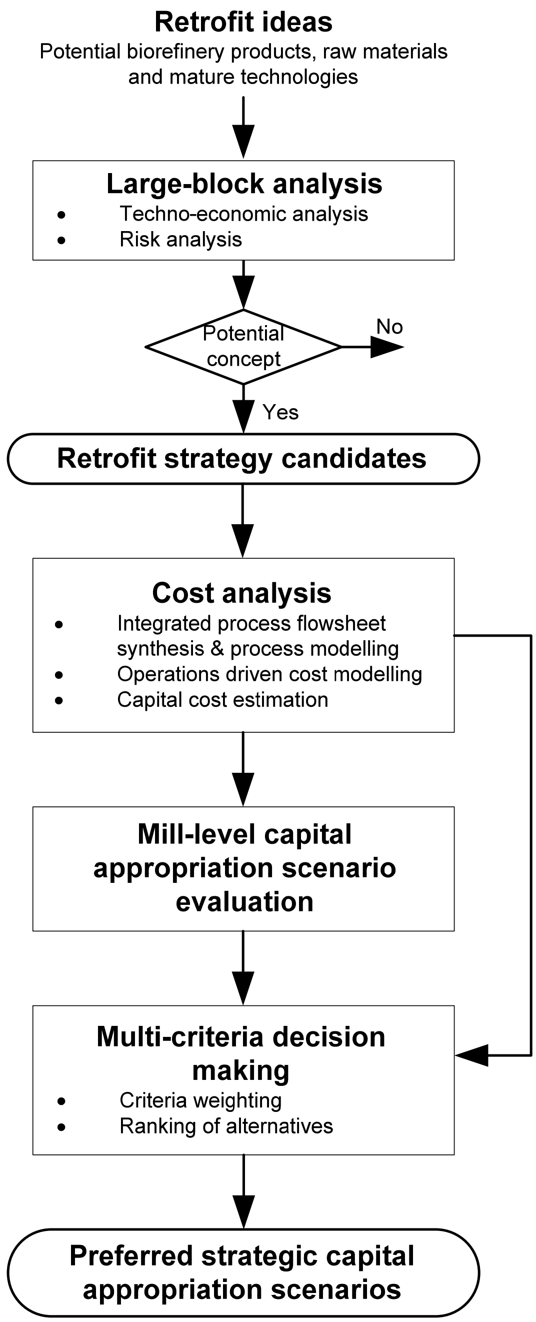

Figure 3. Overall methodology

Large-block analysis

Traditional techno-economic analysis and multivariate stochastic analysis are used for pre-screening of retrofit ideas. In this large-block analysis (see [12] for detailed description), mass and energy balances of the processes implemented in retrofit are considered using input–output-models. Monte-Carlo analysis is used for risk analysis and applied at the lowest cost production capacity of the considered process designs.

Operations-driven cost analysis

Plant-wide steady-state process simulation models are first developed to define the overall mass and energy balances and retrofit project impacts on the existing process conditions and efficiencies. These models are linked to operations-driven cost models that are based on activity-based costing (ABC) principles. The process models provide cost models with resource and activity driver information. These developed cost models are used for product costing and pro-forma cash flow analysis, however the same models currently used for accounting and periodical reporting could also be used.

A three-step sequence is applied for obtaining accurate cost data: 1) development of the base case process and cost models, 2) validation of the base case models using mill data and financial statements and reports, and 3) development of the process and cost models of the retained retrofit cases. The resulting cost models convert the process-impacts into better understanding of cost-impacts, and into pro-forma cash flows reflecting expected future performance of the facility. Monte-Carlo analysis is also used for cash flow risk analysis. A more detailed illustration of the cost model structure is shown in Figure 4.

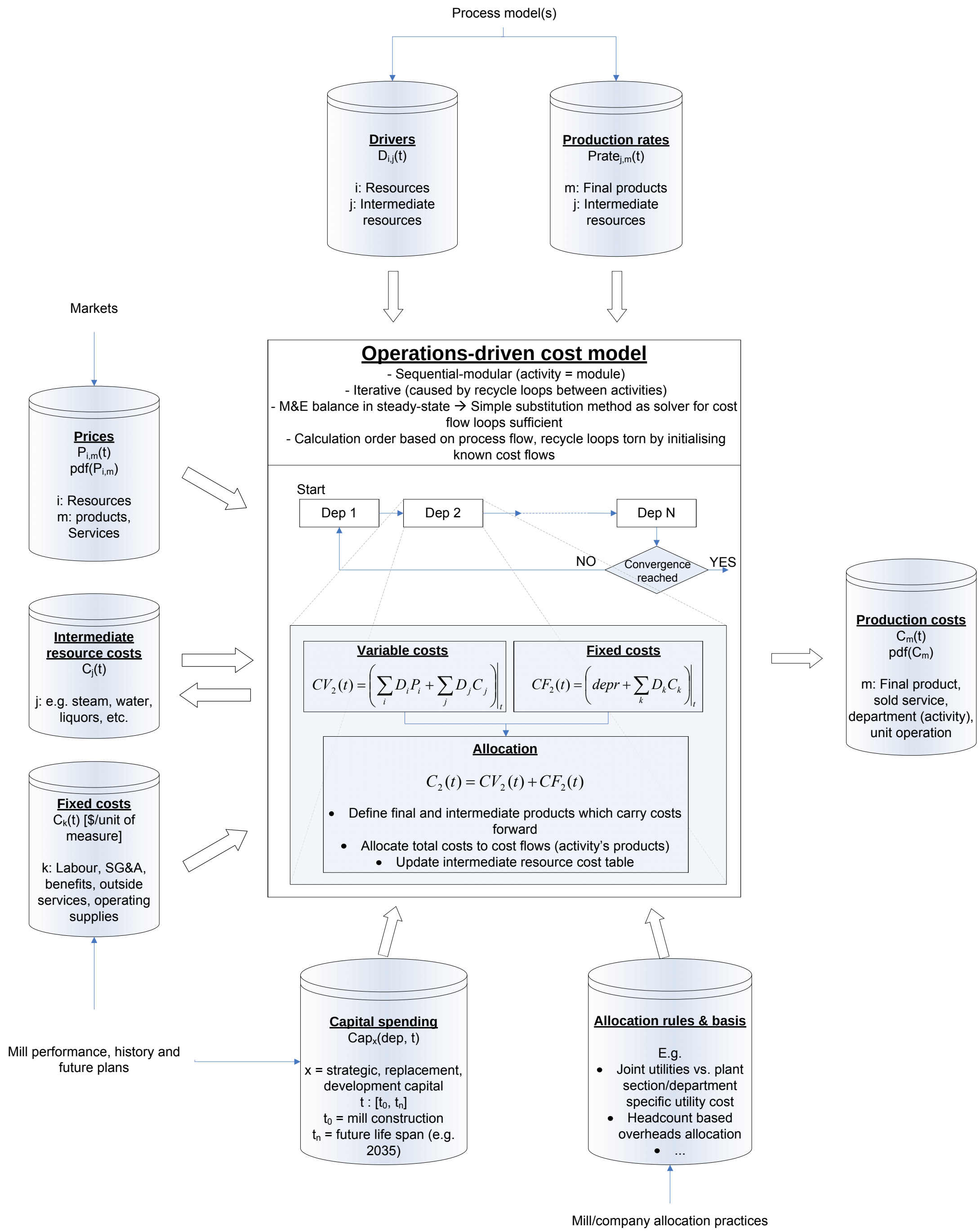

Figure 4. The structure of a cost model for retrofit capital appropriation

Retrofit analysis at the mill level

Contextually relevant economic performance criteria and their measures are identified through understanding of the key performance factors and the business environment. Examples of these key factors are product cost breakdowns, cost competitiveness, location specific uncertainties in business environment such as feedstock and product markets, and criteria for capital performance that stakeholders and investors use in investment decision making. The measures are evaluated based on the pro-forma cash flow statements calculated using the operations-driven costing.

Multi-criteria decision making

A multi-criteria decision making (MCDM) method is applied for obtaining the attribute preferences (weights) for the identified criteria. Multi-attribute utility theory (MAUT) was used as MCDM method, and a panel-based trade-off technique was selected to be used for the weighting because of its easy understanding and implementation. In the trade-off process, the panel members individually compare each criterion to the most important criterion selected by the panel in unison. Comparisons are made as trade-offs: the panelist estimates an attribute score of the most important criterion that makes him feel it indifferent to the other criterion at its maximum score. These trade-offs were assumed to be valid through the ranges of attribute values, thus the criteria are mutually preference independent in the analysis context. Furthermore, the utilities developed from the trade-off values were assumed to be linear between the attribute boundaries, reflecting risk-neutrality of the decision making panel. The average and the standard deviations of the relative importance of all criteria are obtained as a result.

Case study

Integration of biorefinery into a North-American hardwood kraft pulp and paper mill was considered as a case study. Different types of raw materials suitable for a biorefinery surround the case mill, and potential end-users for the bio-products are in the vicinity. Total of 42 feedstock-process-product combinations for production of bioethanol, mixed alcohols and Fischer-Tropsch liquids (FTL) for fuels or waxes were initially identified with the case mill as potential retrofit alternatives for pre-screening. These alternatives used as feedstock woody biomass, pulpwood, hemicelluloses, lignin, corn, corn stover or food processing wastes [11, 12].

The retained biorefinery designs after pre-screening using internal rate of return (IRR) and downside project profitability as screening criteria, and modernization project identified by the case mill are described in Table 1. These were further analyzed using the developed SID making methodology.

Table 1. Retained retrofit capital investment alternatives

Feedstock	Process description	Products	Design capacity	Feedstock capacity
Pulpwood	Modern Kraft pulping process and chemical recovery cycle utilizing maximum amount of existing pulping process equipment	***Kraft pulp***	1650 BDT pulp/day (35% increase from base case)	1.5 million bdt/year
Hemicellulose extract	Near-neutral green-liquor extraction Acid hydrolysis Liquid-liquid separation Fermentation & distillation	***Ethanol*** Acetic acid Furfural	base case – 23 ML/year	10% of pulp wood
			modernized – 30 ML/year	10% of pulp wood
Corn stover Co-processed with kraft pulp, using mill infrastructure to maximum extent	Biochemical lignocellulosic ethanol: Dilute acid pre-treatment Enzymatic hydrolysis Fermentation & distillation	***Ethanol*** Organic solid residue	95 ML/year	0.25 million bdt/year
			379 ML/year	1 million bdt/year
Forest residues Bark co-processed with kraft pulp, using mill infrastructure to maximum extent	Thermochemical Fischer-Tropsch: Drying & grinding Steam reforming Syngas cleaning and compression FT-synthesis	***FT-liquids*** Energy	37 500 bdt/year	0.25 million bdt/year
			150 000 bdt/year	1 million bdt/year

Results and discussion

The main results from the case study application of the overall methodology are discussed in the following sub-sections, more details of individual analysis steps and results can be found from [11, 12] for the pre-screening, from [51, 52] for the operations-driven cost modelling, and from [53] for the investment decision making.

Retrofit project pre-screening

Probability distributions for uncorrelated uncertain external factors identified using sensitivity analysis were assessed using publicly available data. The alternatives considered in capital appropriation were at relatively high technological development level and the markets for the products are existing. Thus, process and market maturity-based uncertainties could be excluded from the pre-screening analysis.

The project risk was assessed using Monte-Carlo analysis (5000 cash flow series iterations) using internal rate of return (IRR) as profitability measure. Based on the results, some of the scenarios are not profitable under the economic assumptions, and can be screened out from further analyses. The risk measure used was downside project profitability (profitability obtained with 97.5% certainty) which is relatively important metric in general in SID making in manufacturing industries [38]. The resulting list of most promising retrofit projects ranked based on expected risk-free project profitability is shown in Table 2.

Table 2. Most promising design scenarios based on ranking using IRR

Feedstock, product (identifying process step)	Capacity (ML/year)	IRR	standard deviation	Downside IRR
Corn stover, Mixed alcohols (steam reforming)	379	13.0 %	2.1 %	8.7 %
Lignin, Ethanol + higher alcohols (steam reforming)	189	12.3 %	2.0 %	8.2 %
Biomass, Mixed alcohols (steam reforming)	95	8.7 %	1.6 %	5.5 %
Hemicelluloses, Ethanol + acetic acid (near-neutral hemicellulose extraction prior-to-pulping)	19	6.9 %	0.9 %	5.0 %
Biomass, Ethanol + higher alcohols (steam reforming)	95	5.9 %	1.5 %	2.9 %
Corn stover, Ethanol + higher alcohols (steam reforming)	379	3.4 %	2.0 %	-0.6 %
Pulp wood, Mixed alcohols (steam reforming)	189	3.4 %	7.3 %	-11.1 %
Lignin, Ethanol + higher alcohols (gasification)	189	1.5 %	3.3 %	-5.1 %
Corn stover, Mixed alcohols (gasification)	379	0.7 %	3.4 %	-6.0 %
Biomass, F-T liquids (gasification)	95	0.6 %	2.1 %	-3.5 %

When comparing this ranking and the relative risk in each of the retrofit projects (standard deviation), it is clear that the most promising alternatives are also more uncertain than some of the lower profitability projects. Moreover, some of the projects have significantly higher risk even though same technology and products are considered. This results from different feedstock cost uncertainty. We used this knowledge in screening out higher risk retrofit scenarios in addition to low performance scenarios to arrive at the scenarios listed in Table 1.

Retrofit project cost-impact analysis

The operations-driven cost modelling approach provides the production costs of all products. The base case process simulation model was validated using process data. The base case production costs were validated using monthly financial statements from the simulation model input data time period. The cost-impacts shown in Figure 5 (including all added cost or benefits realized at the integrated paper mill) varied between 0.2% increase and 19.2% decrease measured from the base case production costs. Thus, significant cost changes resulted from the retrofit projects, largest cost reduction was obtained in simultaneous mill modernization and biorefinery implementation, resulting mainly from the additional capacity in all energy systems (boilers, turbines) and increased electricity production due to better energy efficiency of the pulp mill.

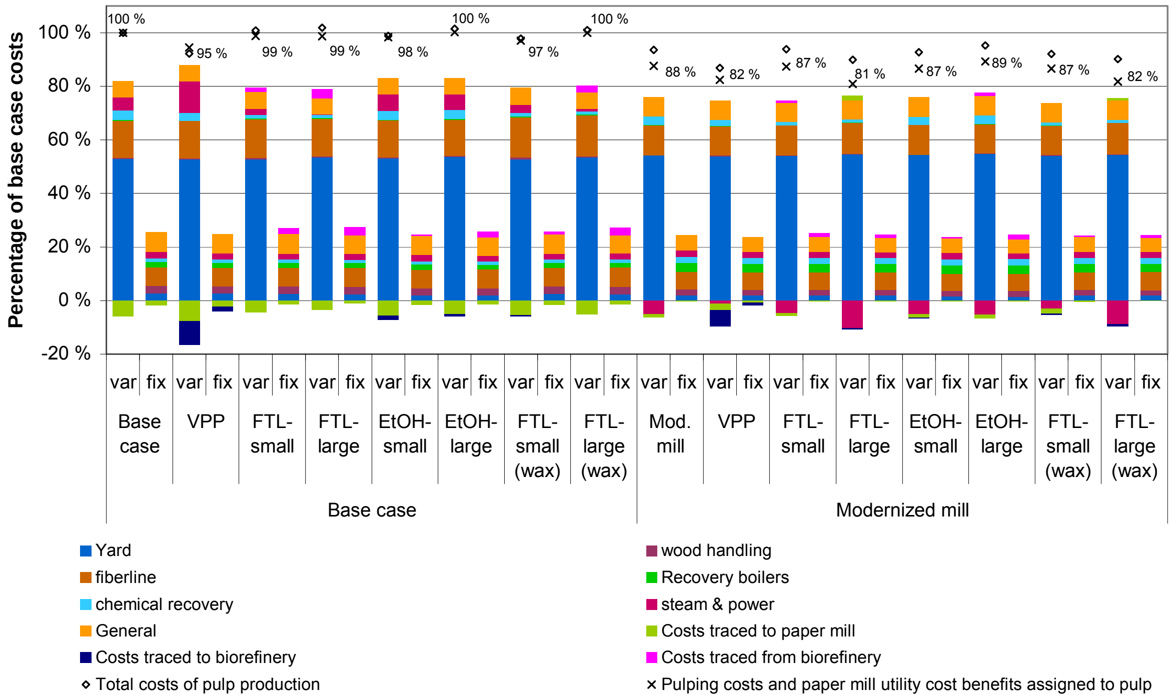

Figure 5. Variable and fixed pulp production costs in retained retrofit scenarios

The bioproduct production costs (Figure 6) in the same retrofit scenarios show that even though the feedstock costs are the main contributor to the total biofuel production costs, both variable and fixed cost that are transferred between the pulp mill activities and the biorefinery activities impact significantly the total costs.

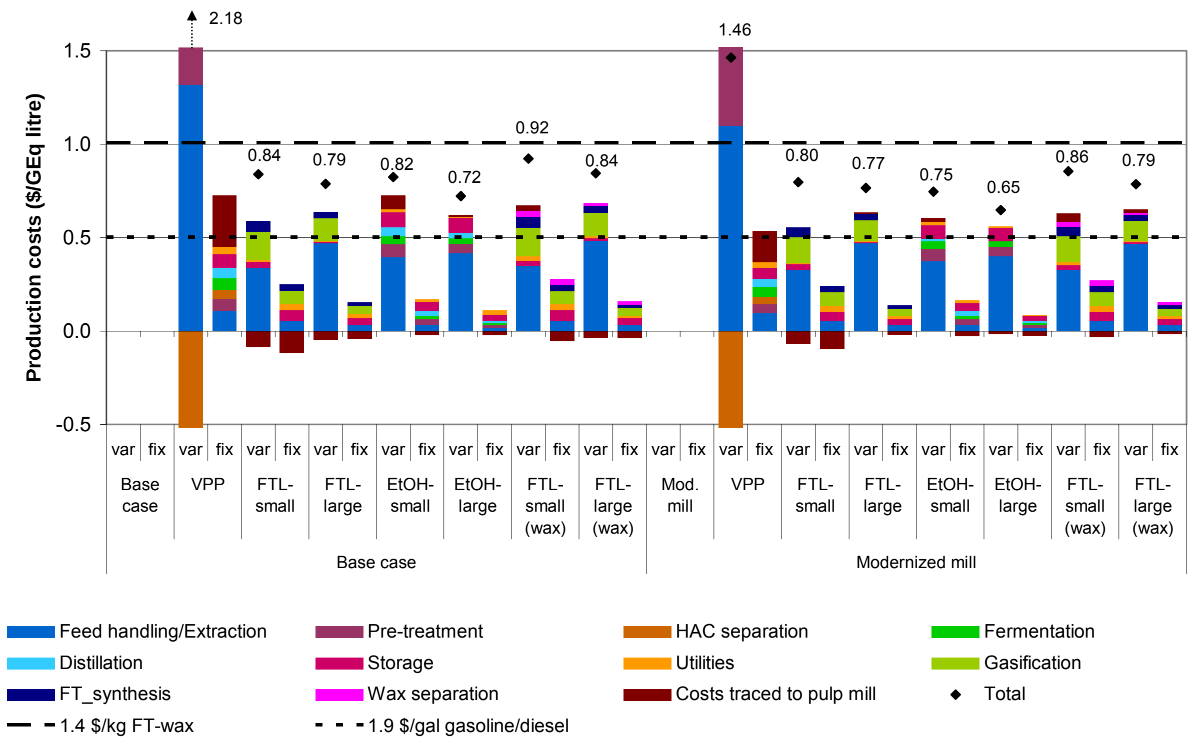

Figure 6. Variable and fixed bio-product production costs in retained retrofit scenarios

Energy costs are an important factor for good economic performance of the forest biorefinery and these costs vary significantly between retrofit scenarios. Three factors, steam demand, available fuel mix, and energy system constraints mainly define these costs. A combined effect of them is partly illustrated in Figure 5 as the costs of steam & power department varying from ~10% of the reference pulp production costs to ~10% revenue (measured as percentage of reference pulp production costs), and as the costs traced to paper mill (consists mainly of energy costs/revenues).

Comparing the production costs of biofuels between the large-block analysis and the advanced costing, we obtained different results (Table 3). Major reasons for the differences are in the assumptions of energy costs (constant in traditional analysis, marginal steam prices), and constraints in the case mill's energy system (boiler heat loads and steam turbines). In traditional analysis, these were over-estimating the energy system potential and therefore under-estimating the production costs. Secondly, no additional workforce was assumed to be required in the traditional analysis whereas in the analysis using the developed costing framework, the available workforce at the mill was systematically assessed and extra labor was considered to be used when needed. Thus, the level of detail used in traditionally in techno-economic analysis for SID making might not suffice.

Table 3. Comparison of traditional costing and operations-driven costing: Biofuel production costs in selected retrofit scenarios. Costs are measured in dollars per gasoline equivalent (Geq) liter

Design scenario (integrated into base case mill)	Traditional analysis ($/Liter Geq)	Operations-driven cost analysis ($/Liter Geq) [9]
VPP	0.69	1.3
Small FTL process	0.59	0.77
Large corn stover-to-ethanol process	0.55	0.72

Moreover, we analyzed the impacts of changing production rate on the bio-product production costs (Figure 7), and on the other hand the impacts of shifting an intermediate product of the biorefinery between energy and biofuels production (Figure 8) using the costing framework.

[9] pulp & paper production cost benefits relative to base case are assigned to biofuel production costs for commensurate comparison

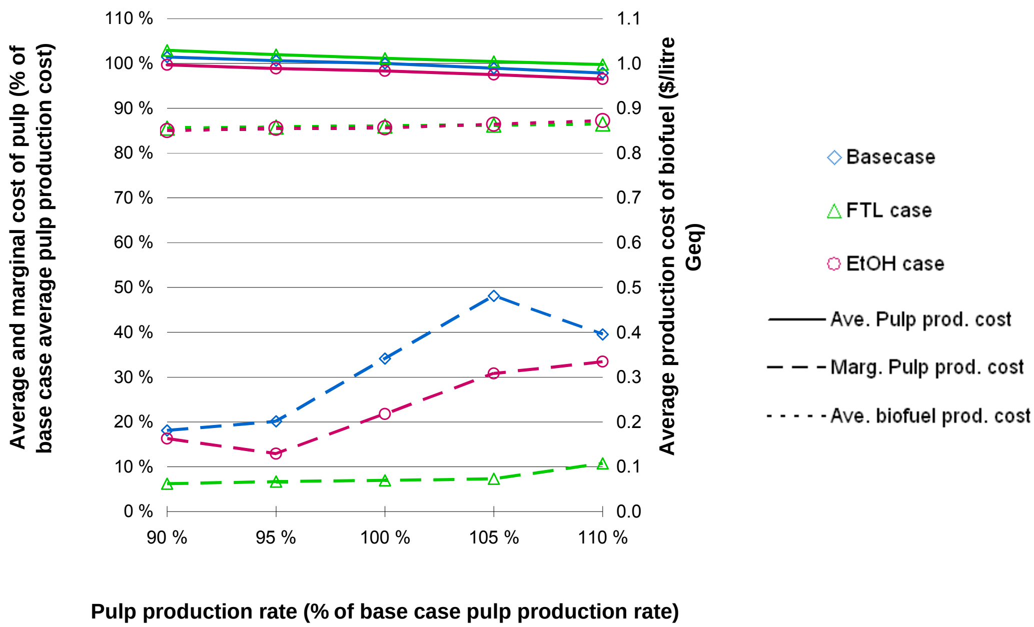

Figure 7. Average and marginal production costs of pulp and average biofuel production costs as function of pulp production rate in three example scenarios

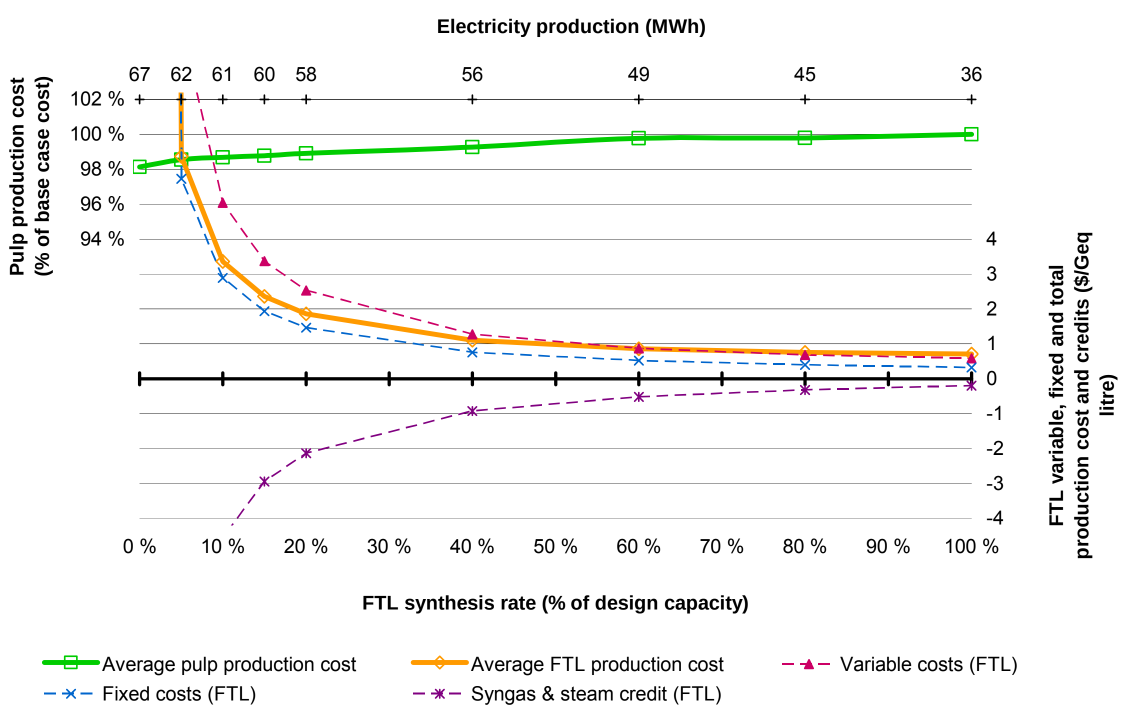

Figure 8. Production costs in inherently flexible FTL production system as function of FTL synthesis rate

The results of our analysis illustrate well, that the costing framework enables cost analysis under different demand, price, and operating conditions. Marginal costing, standard full costing, and margins analysis using individual product profit margins or total margin in different operating regimes and temporarily increased or decreased production of one or more products is possible. We did not use this information in the SID making step of the methodology, but it has potential in analyzing the responsiveness of the investment strategies against changing business environment, and, in designing the production capacity and flexibility of the FBR.

Capital appropriation decision making

First, we identified the set of mutually preference independent criteria for SID making, and the metrics for these criteria. The set of criteria is illustrated in Figure 9 with the used decision making structure: the criteria are considered at the same decision making level in order to avoid ambiguous aggregation and potential difficulties in understanding the aggregated criteria. Moreover, the measures of the criteria are shown.

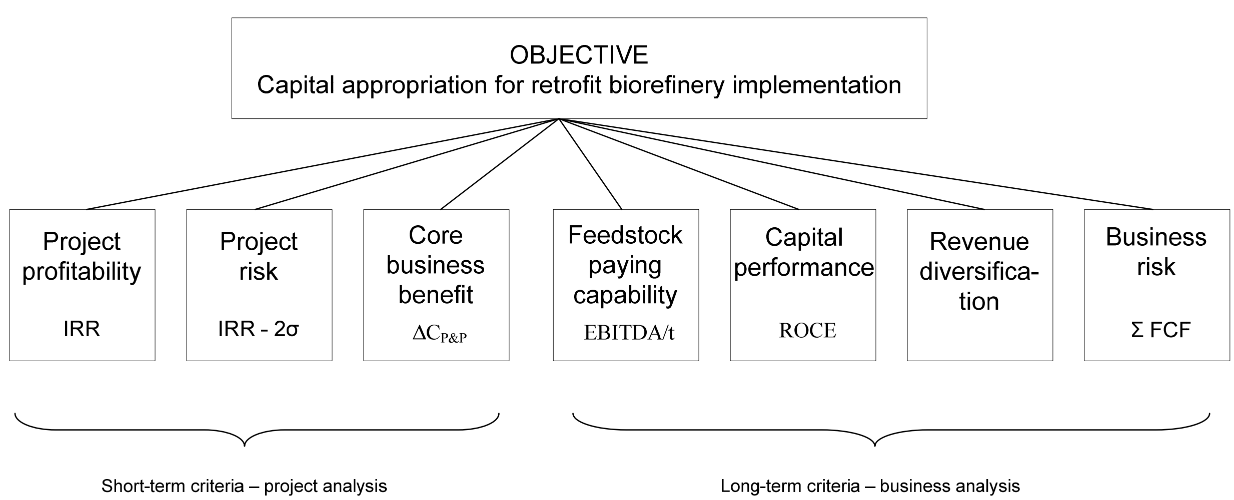

Figure 9. Decision structure for the retrofit design problem

Eight people from the case mill (mill manager, process engineers, R&D and strategic planning personnel) involved in investment decision making were assembled for an MCDM panel. The resulting decision weights based on average trade-off values of the panel, and the standard deviation in the weights resulting from sensitivity analysis (Monte-Carlo analysis, probability distributions fitted to panelists' trade-off values for each criterion) are shown in Figure 10.

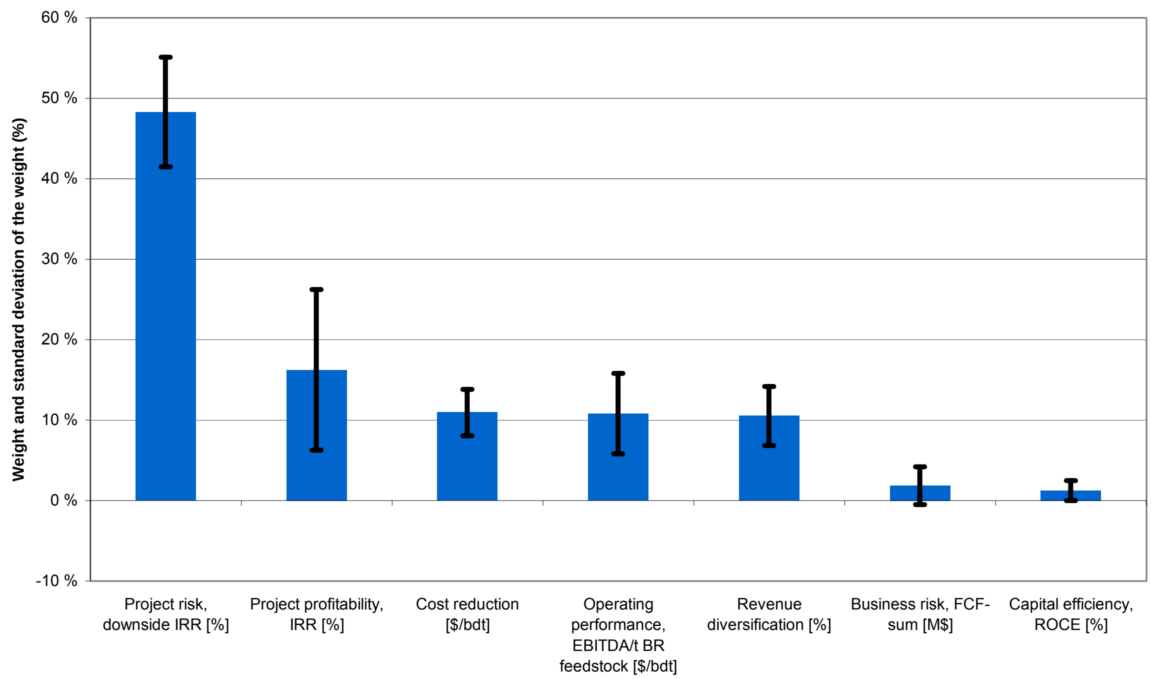

Figure 10. Decision weights based on average trade-off values and their standard deviations calculated using Monte-Carlo analysis

The project performance criteria (three highest ranked criteria) are dominating, constituting over 75% of the total weight on average. Moreover, for the panelists the capital efficiency and capability to respond to unexpected drastic changes in the business environment by re-investments and new strategic investments was not important. This reflects both the company practices and potentially the panel orientation towards short-term decision making.

Utilizing the weights and the evaluated attribute intensities, the overall utility is obtained using additive utility function.

$$U(x) = \sum_i w_i u_i(x_i) \qquad (1)$$

where $U(x)$ is the total utility, w_i is a weight of the attribute i, and $u_i(x_i)$ is the utility of the attribute i. The summation goes through all decision making attributes i.

This overall utility represents the ranking of the alternatives (Figure 11).

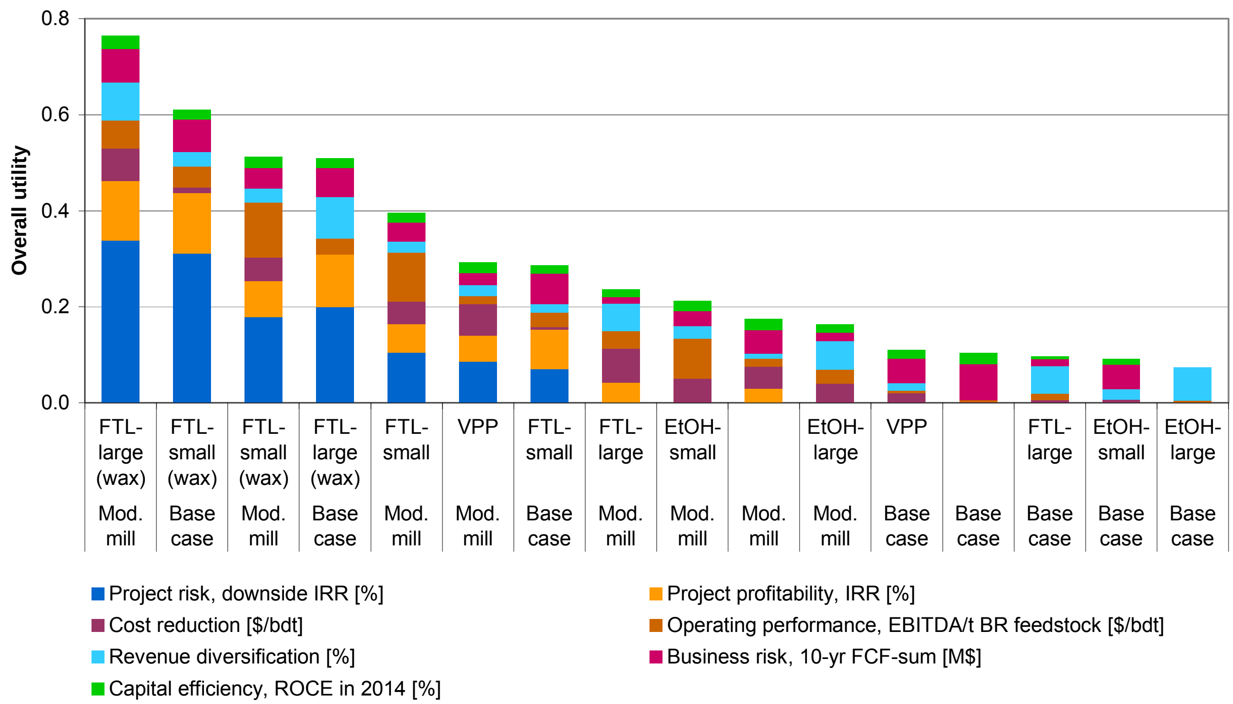

Figure 11. Ranking of capital investment scenarios based on overall utility value

The most important criterion clearly dominates the ranking. However, other attributes also effect the ranking. On one hand, between the most preferred alternatives a more balanced decision is obtained (all criteria contribute to the overall utility). The overall ranking follows the ranking based on project-based criteria, except in the case of 3rd and 4th most preferred alternatives where good operating performance of 3rd alternative emphasizes the importance of strategic performance criteria. On the other hand, for the lower ranked alternatives with less balanced overall utilities, differences between impacts of individual strategic criteria on overall ranking are significant.

Conclusions

The capital intensity of the P&P and biorefinery processes are important factors for forest biorefinery decision making. Moreover, the relatively low capital efficiency of the P&P industry compared to other capital intensive manufacturing industries also makes this industry non-attractive to investors [54], and can potentially hinder the implementation of the forest biorefinery. This combined with the uncertainties in the business environment of the forest biorefinery makes it imperative to apply systematic risk analysis and effective decision making process in strategic investment decision making for forest biorefinery.

Often higher returns are expected from higher risk investment projects, and thus, a subjective discounting is used when analyzing economic performance of potential investment projects. Moreover, different scoring –based investment opportunity analyses including subjective risk terms are applied to account for technological and market uncertainties. Thus, risk analysis is recognized to be important but it is not explicitly and systematically considered in the decision making.

The objective of this work was therefore to develop a methodology to improve the link between retrofit process design, cost accounting and capital investment decision making activities for enhances investment decision making for forest biorefinery under uncertainties. The methodology consists of step-wise decision making, starting with pre-screening of retrofit design alternatives based on traditional techno-economics and risk analysis, followed by an advanced decision making procedure. The second decision making step uses a novel framework combining process design and simulation to strategic investment decision making process through cost accounting models based on activity-based costing principles. The operations-driven cost models that are linked to process simulation are able to represent accurately the manufacturing costs of all products after retrofit biorefinery implementation, and on the other hand, these models are able to provide useful and accurate financial data for measures of short- and long-term performance of the projects and the facility for strategic investment decision making. Moreover, systematic risk analysis using stochastic multivariate analysis can be utilized since all performance metrics are explicitly quantified.

Results of the case study application of the methodology showed, that systematic analysis of external uncertainties using multivariate stochastic analysis enables a more objective assessment of the uncertainties. Furthermore, the analysis results of the retained retrofit design alternatives using the developed framework clearly quantified the cost-impacts of the retrofit projects, which in the case of normal process design and capital appropriation process would be available only for the implemented project when it is operating. These impacts varied between alternatives because of different integration potential and system constraints. Assessment of the importance of key performance criteria using a panel-based MCDM showed that even though project performance criteria were preferred, facility-level performance had an important role in the overall ranking of the retrofit alternatives. Moreover, the final ranking of the alternatives differed from that of using only a single criterion, project profitability. In addition, the dispersion in the attribute importance preferences of mill and company personnel from varying positions demonstrated the multi-faceted nature of this strategic investment decision making problem.

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) Environmental Design Engineering Chair at École Polytechnique de Montréal, and by a research project at VTT Technical Research Centre of Finland in the BioRefine Technology Programme of the Finnish Funding Agency for Technology and Innovation (TEKES). We also acknowledge gratefully the industrial partner supplying the case specific data and the industrial experts involved in the development of this methodology.

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APPENDIX E – Feature: Capital appropriation for the forest biorefinery

Capital appropriation for the forest biorefinery

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Many pulp and paper (P&P) companies are investigating their options with biofuel and biochemicals production, but at the same time also making decisions regarding competitiveness of their current products. Competing from the same capital is difficult with projects being technologically and market-wise less developed. Moreover, using performance measures that are commonly applied by forest industry management favours annual capital expenditures over long-term strategic capital spending and can be incapable of quantifying underlying risks of both scenarios.

The objectives of this paper are to identify a set of necessary financial performance criteria for capital investment project appraisal, and to present a method for measuring and weighting these criteria in decision making for screening of capital appropriation alternatives using a case study in above described context.

Main factors of forest biorefinery performance

Forest biorefinery (FBR) strategies can potentially benefit from retrofit implementation into existing facilities, however this benefit is mill specific. Moreover, the integration leads to changes in production costs of P&P products. These changes can differ significantly between FBR strategies due to the different process and business level integration potential of the biorefinery processes. For instance, different energy demand and level of sharing the labour and overhead costs can impact the P&P product production costs.

Apart from overall cost competitive production of all products in a forest biorefinery, some important cost factors require special attention in decision making for FBR. Major cost factors for both P&P products and envisioned bio-products are feedstock costs and fixed operating costs (Figure 1). Feedstock costs can vary significantly especially in the case of biorefinery, this variation is a results of competition of the raw material, transportation cost changes (oil price-dependent) and process reliability. Fixed costs on the other hand depend on the labour-intensity and overall condition of the asset.

In addition to project profitability, in the long run the overall business should stay productive. This is dependent on the efficiencies of the production system and on external factors such as product prices. The system efficiencies are more predictable whereas many external factors are volatile and unpredictable by nature. The volatility in prices could potentially be absorbed by a strategy in which the products are sold to independent markets. Thus, the capability to mitigate revenue losses due to market volatility depends partly on the level of revenue diversification relative to an appropriate level for the mill.

In general, uncertainties in external factors (e.g. in long-term product and feedstock price trends) manifest themselves differently in different investment strategies and can lead to unwanted outcomes. Moreover, conceptual design capital cost estimates of lower technological maturity level biorefinery processes compared to traditional P&P industry investment projects have higher uncertainty. These can result in lower project profitability than expected, or in low overall performance of the facility leading to a shut-down. These uncertainties are mainly driven by the markets, maturity of process technologies and condition of existing assets.

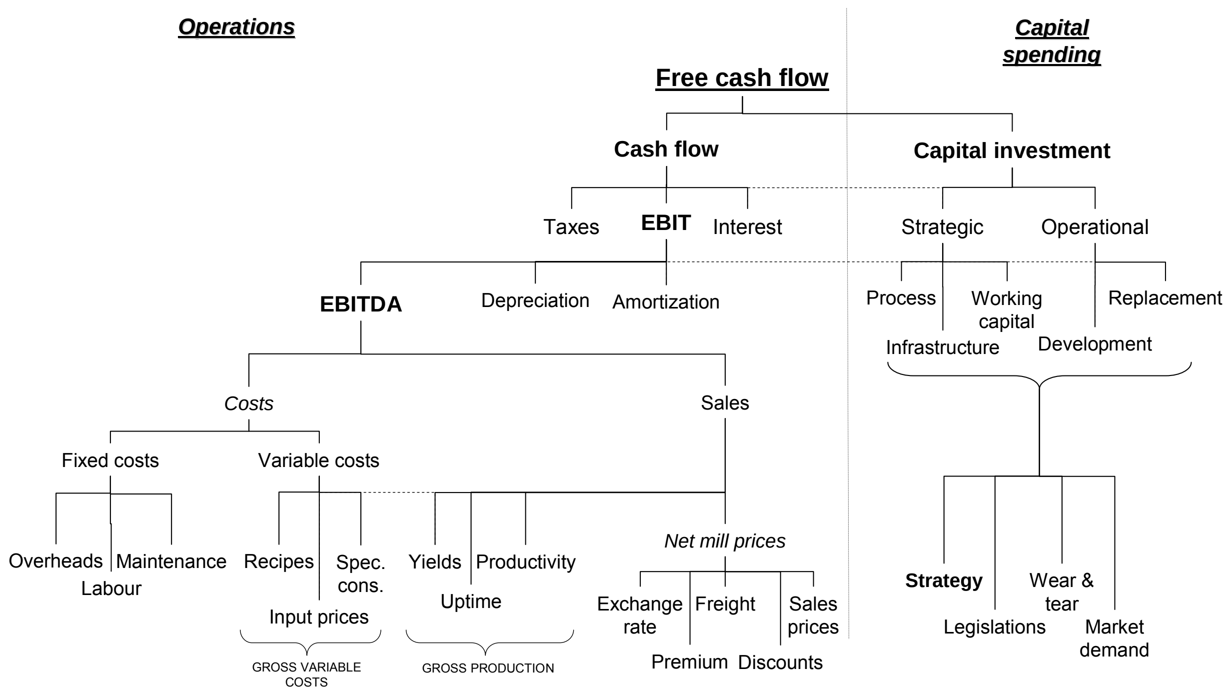

Figure 1. Factors impacting performance of operations and capital spending

Measuring the performance of a strategy

Criteria and their measures

Several metrics are used for measuring project and business performance: design analysis of retrofit projects often use economic potential, payback period, return on investment, gross profit, minimum selling price, internal rate of return (IRR) or net present value (NPV) as measure. These criteria are simple indicators of project's financial performance, except IRR and NPV that consider discounted cash flows over the project's lifetime and can better represent the "true" performance. Performance analysis by investors and creditors at business level and by management at facility level, measures capital spending on the entire facility and costs and revenues of all products instead of only considering one project separately. For example, return on invested capital, return on capital, or return on capital employed (ROCE) are often used capital performance measures. Earnings before interest and taxes, or earnings before interest, taxes, depreciation and amortization (EBITDA) on the other hand exclude capital related costs and thus measure only the operating performance of the facility.

The risk of not obtaining targeted performance level or worst-case scenario performance can also be quantified using for example sensitivity or scenario analysis, or multivariate stochastic analysis and statistical measures such as variance or standard deviation. Thus, the same performance measure is used under different assumptions.

These traditional project and business performance metrics are not capable of measuring directly the key factors of strategic investment in biorefinery and traditional P&P projects. Using several criteria, specifically adapted to this context will enable commensurate and objective representation of both traditional lower technological risk projects, and business transforming FBR projects. In Table 1, such set of criteria with suitable metrics are defined. Moreover, interpretation of these criteria elaborated in the case study context is given.

Table 1. Definition of the proposed set of decision making criteria

	Definition	Measure & units	Interpretation by the case study panel
1	*Project profitability* Expected risk-free project profitability	Internal rate of return (IRR-%) $NPV = \sum_{t=0}^{20} \frac{CF_t}{(1+IRR)^t} = 0$	Traditional capital allocation method which is commonly used as a screening metric. Using expected future trends makes this criterion realistically consider the most probable future returns. As a relative measure the knowledge of the total capital investment costs is needed for comparison between large strategic and smaller annual capital projects
2	*Project risk* Worst-case scenario project profitability based on Monte-Carlo analysis	Downside IRR (%), 97.5% certainty for profitability $IRR_{downside} = IRR_{expected} - 2\sigma$ $\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2}$	Worst-case scenario profitability indicates what is the combined sensitivity of project performance on all uncertain market variables and project capital cost estimate. The focus is on raw material and product market uncertainties. Maturity of technologies and markets in the capital appropriation level is considered to be similar for all alternatives. Thus, significantly less developed processes should have been already screened-out. Capital cost estimation uncertainty captures the basic difference between known technologies such as P&P process equipment and developing technologies like biorefinery processes.
3	*Core business benefit* Decrease in core product production costs	Change in pulp and paper operating costs ($/bdt pulp) $\Delta C = \Delta C_{pulp} + \Delta C_{paper}$	This measures the cost impacts of integration on core business: it indicates how well the project implementation will help in short term to stay competitive with core products. It is also included as cost saving in project performance measure. It can be an important measure for mills struggling with their high costs and having significant integration potential, whereas for modern mills with low costs this might not be as critical.
4	*Feedstock paying capability* Ability to pay more for raw material	Earnings before interest, tax, depreciation and amortization (EBITDA) per feedstock mass flow ($/bdt feedstock)	The feedstock costs take significant share of all production costs, and future competition of bio-based feedstocks is going to change the raw material prices. High amount of cash generated from operations that can be used for absorbing the possibly fast and significantly increasing raw material costs is therefore of significant importance to be able to stay operational in longer term.
5	*Capital efficiency* Return on the capital spent in the asset	Return on capital employed – ROCE (%) $ROCE = \frac{EBIT}{Capital\,employed}$	Mill and company management measures the overall asset performance using this measure. It considers all past capital spending on fixed asset and can therefore be used to track the development of capital spending efficiency in time. High ROCE indicates high before tax return on depreciated asset value, measuring the current asset's relative ability to make money.
6	*Revenue diversification* Ability to absorb changes in product markets	Share of revenues from new products from total revenues (%)	More diversified revenue basis is better able to absorb price variations in one or more products in portfolio. Non-correlated products can better mitigate price volatility related risk. It is a strategic criterion that is not often highly appreciated in pulp & paper industry where specialization in products with correlated market dynamics and lowering production costs have been trends.
7	*Business risk* Capability to react to business environment changes in long term in the capital spending scenario	Sum of free cash flow (FCF) from all operations (M$) until the first year with negative FCF	The capability to respond to unexpected drastic changes in the business environment, such as significantly lower demand of products or new regulations, by re-investment or new strategic investments. The base case scenario also poses challenges that are difficult to assess (not included in the measure but needs to be considered when defining the criteria importance): technological obsolescence and unexpected system failures leading to high repair and maintenance costs.

What is the importance of an individual criterion?

Carr et al.[1] investigated the trends how strategy impinges on management accounting practices in both stable and dynamic market settings. For example, geographic region implies some preferences and use of criteria because of infrastructure age and financial structure, or, different business orientation (e.g. market creator vs. refocuser) allows different hurdle rates and payback period expectation. Understanding these underlying differences and the link to overall strategy of a company can help explaining the decision making preferences. Yet, every company and mill needs to make their decisions based on proper evaluation of alternatives using most suitable criteria weighted in their relevant business context. E.g. for specific market position or segment the renewal of revenue basis might not be important for stable income, or, if biomass supply-chain and market are well established the biomass paying capability is less important for individual project. On the other hand, when comparing multiple strategies these might become important factors and should not be excluded from the analysis.

The survey of Hogaboam and Shook [2] examined how different traditional performance measures are used in US forest industry capital budgeting and rationing, concluding that IRR and NPV are the main techniques used. They also confirm the known practices in risk analysis: sensitivity analysis and subjective adjustment of cash flows are the most commonly used. Major uncertainties considered are the risk of not obtaining target return, uncertainty of market potential and uncertainty of entering an inexperienced area, however these are measured subjectively.

Evaluating the measures and weighting the criteria – cost accounting and structured decision making

Evaluation of the performance measures of Table 1 for strategic investment alternatives at reliable accuracy level is best achieved by using cost accounting methods used by the industry such as activity-based costing (ABC). A systematic framework linking process simulation and modelling with ABC has been proposed by the authors to properly evaluate the cost implications of retrofit biorefinery integration [3, 4]. Existing ABC models can be utilized, thus the current business is modelled as accurately as it is calculated for monthly and annual reporting purposes.

The decision making process should also involve all relevant stakeholders to obtain a balanced opinion of the importance of different criteria. This can be achieved by using panel-based multi-criteria decision making (MCDM) methods.

Case example

The proposed set of criteria (Table 1) was used in the evaluation process of three biorefinery technology strategies and one traditional pulp mill modernization scenario for a North-American integrated hardwood P&P mill. These were promising scenarios based on pre-screening [5, 6]. A panel of eight people from the mill (mill manager, process engineers, R&D and strategic planning personnel) was assembled for weighting the criteria using a trade-off method. In this type of an MCDM, panel members individually compare each criterion to the most important criterion selected by the panel in unison to obtain the relative importance of all criteria.

Considered technology strategies:

- Mill modernization – Current pulp production capacity is increased by 35%

- Corn stover-to-ethanol using co-current dilute-acid pre-hydrolysis and enzymatic hydrolysis. Design capacities: 25 MMGPY (small) and 100 MMGPY (large).
- Fischer-Tropsch liquids (FTL) from forest-based woody biomass. Design capacities: 12 MMGPY (small) and 48 MMGPY (large). Produced FTL can be sold as diesel fuel or the wax fraction separated and sold as FT-wax.
- Hemicelluloses-to-ethanol using near-neutral green liquor extraction of hemicelluloses from hardwood chips before kraft pulping. Design capacities: 6 and 8 MMGPY ethanol and same amount acetic acid for base case and modernized mill correspondingly.

Total of 7 biorefinery scenarios are evaluated as retrofit implementation into the current mill and into modernized mill. Examples of the attribute intensities of these alternatives are illustrated in Figures 2-5.

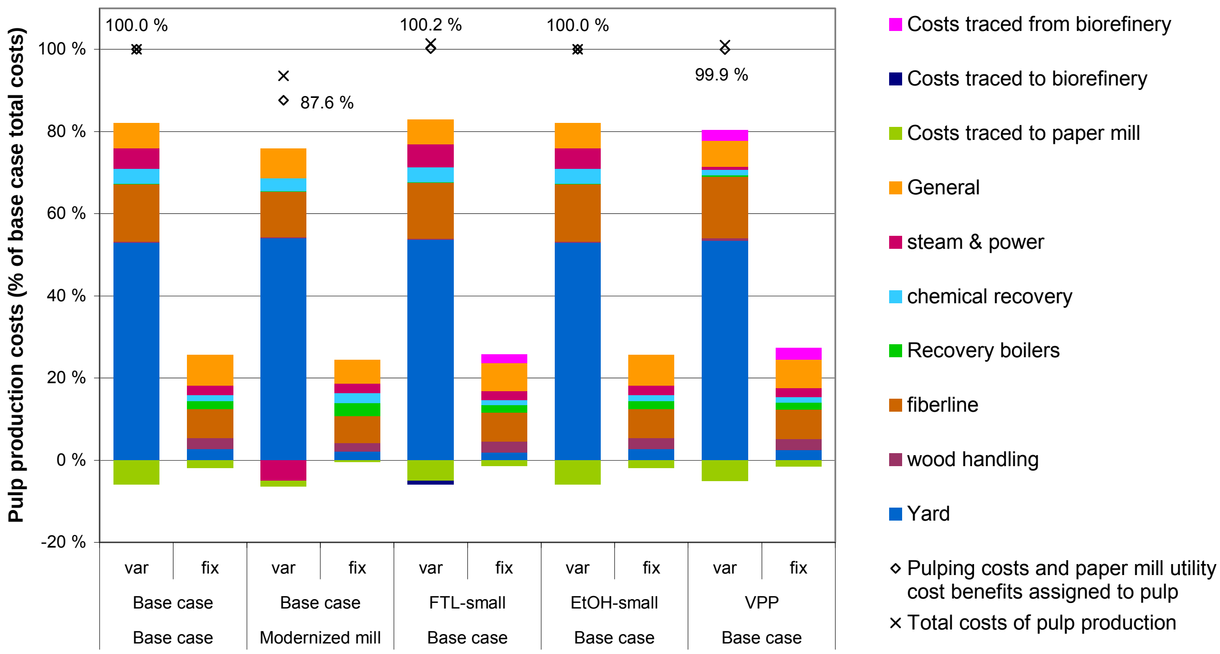

Figure 2. Criterion 3 – Cost benefit of three example retrofit biorefinery implementation and mill modernization projects measured as relative pulp production costs in first year of full operation (2014). Changed costs traced to paper mill are assigned to pulp production costs. No changes in total overhead costs are assumed.

From the example strategies illustrated in Figure 2, the project targeting enhanced cost competitiveness (mill modernization) is able to lower 12.5% the total P&P production costs whereas significantly lower cost changes can be expected from biorefinery implementation projects. However, individual cost categories are impacted substantially also in these cases, for example energy costs vary significantly.

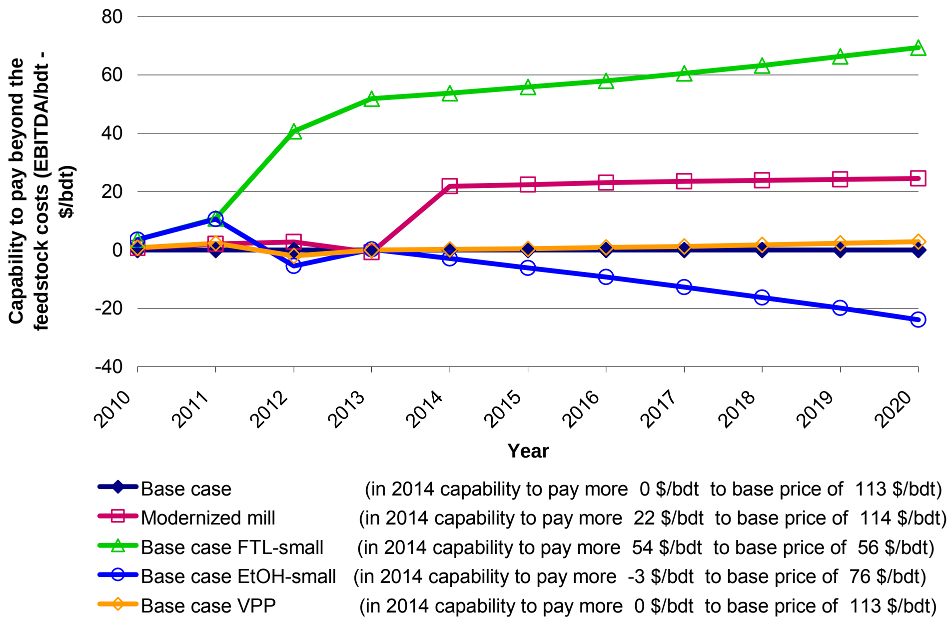

Figure 3. Criterion 4 – feedstock paying capability. Incremental EBITDA to base case EBITDA is allocated to dry ton of feedstock. In traditional project (mill modernization) the feedstock is pulpwood, in biorefinery cases the used biomass (woody biomass in FTL case, corn stover in ethanol case and pulpwood in VPP case). Decision making criterion is the value in first year of full operation (2014).

Under the assumed price scenarios and production related variables (yields, reliability, energy efficiency, productivity, and their future improvement), the cash generated from operations in different capital investment scenarios results in different capability to respond to feedstock price changes. From the illustrated scenarios, FTL production shows much higher potential to respond to changed woody biomass costs compared to ethanol case's corn stover paying capability.

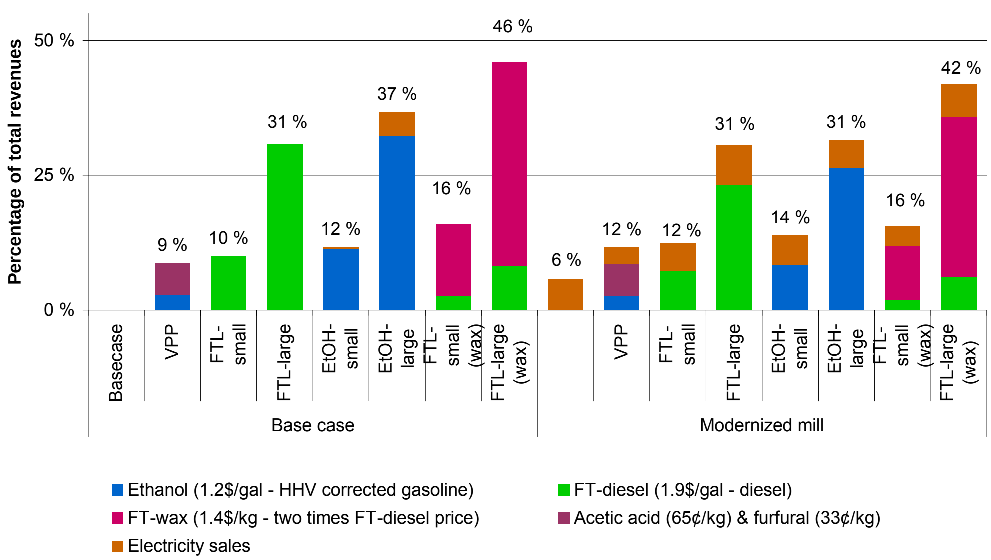

Figure 4. Criterion 6 – Renewal of revenue basis. Adjusted market pulp price was assumed as transfer price for internally used pulp.

High production volume and unit price of the new products increase the relative share of the revenues from those products. The total revenue basis is in this case also dependent on the electricity production potential. Thus, large facility producing highest price product (FTL waxes) and all large scale production with additional electricity production show highest revenue basis renewal.

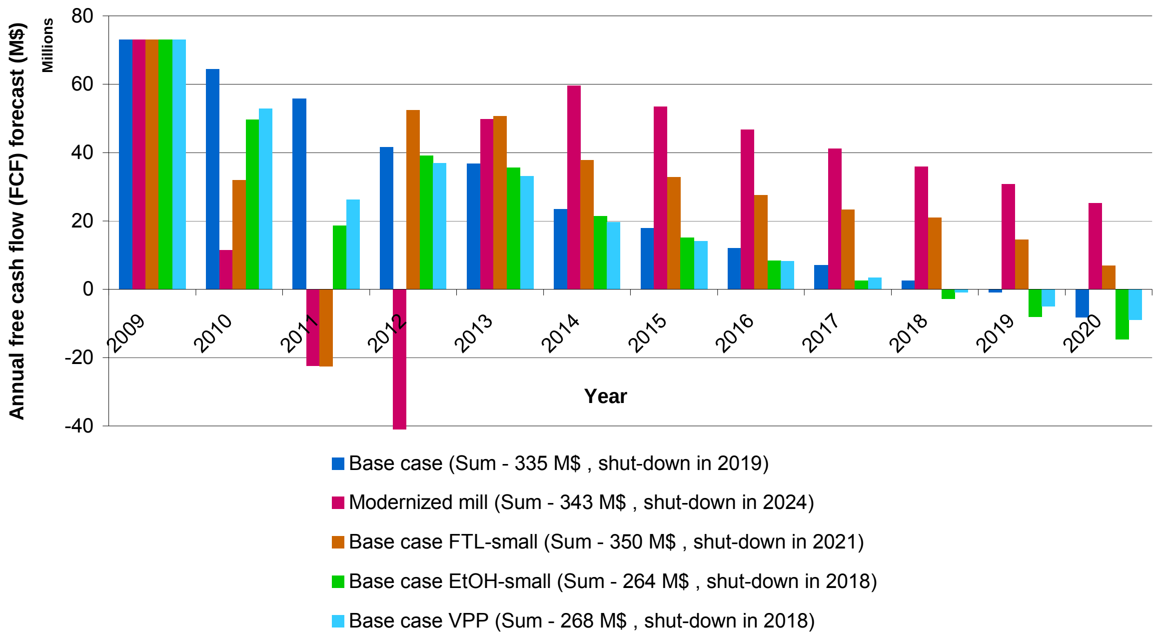

Figure 5. Criterion 7 –free cash flow forecasts. Decision making criterion is calculated as a sum of all free cash flows until negative FCF (shut-down criterion).

As expected, future performance improvements of the pulp mill are not able to overcome alone the product price erosion and the increasing costs (blue bars – base case FCF trend is decreasing). The trend is similar in all scenarios, however better overall performance can increase the total free cash generated in long-term. This can be further re-invested in the facility. Small FTL-production scenario does not generate as much free cash flow as the mill modernization but due to its lower investment requirement it offers long future for the mill and enables same level of future re-investments as the mill modernization.

The relative importance of criteria for the mill panel is shown in Table 2.

Table 2. Weights and standard deviations of criteria based on panel members' trade-off values and sensitivity analysis organized in decreasing order of importance.

Ranking	Criterion	Weight (%)	Standard deviation
1	Project risk	48.3	6.8
2	Project profitability	16.3	10.0
3	Cost reduction	11.0	2.9
4	Revenue diversification	10.8	5.0
5	Operating performance	10.5	3.7
6	Business risk	1.9	2.4
7	Capital efficiency	1.2	1.2

The weighting shows clearly the importance of project performance criteria in this decision making context for the case mill panel. Extremely important to them was the worst-case scenario project performance. On the other hand, capital efficiency as a decision making criterion was not seen important, partly because of the company practices.

The resulting ranking of strategic alternatives is presented in Figure 6, and the sensitivity of the overall utility (or ranking) on the variation in individual panellist's preferences in Figure 7.

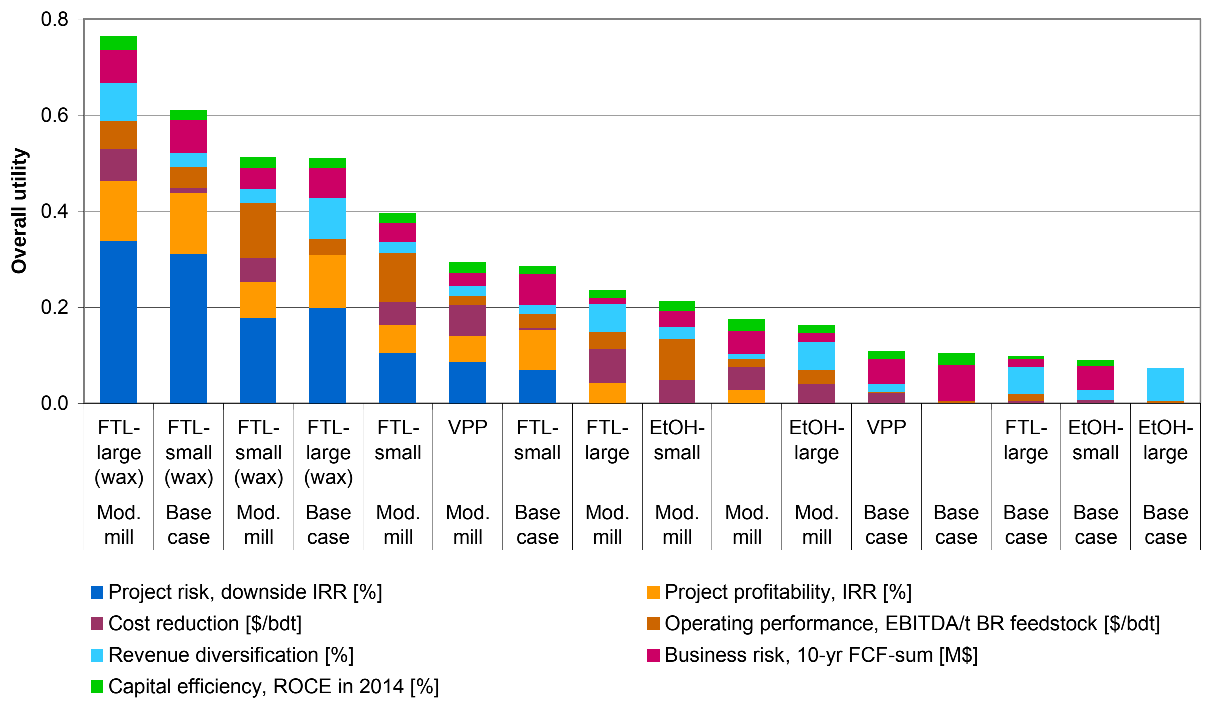

Figure 6. Ranking of all considered capital spending scenarios (overall utility) and the impacts of individual criteria and their weights on the overall ranking: the height of a bar represents one criterion relative to total height of the stacked column. The alternative with highest overall utility is the most promising

Because of the high importance of the worst-case scenario project performance assessed by the panel, the ranking of the strategies follows strongly that criterion. However, the importance of the other criteria is important and emphasized in the case of large bioproduct production capacity strategies: revenue diversification, operating performance and cost reduction become more important factors for the overall ranking. Relatively high consensus (low standard deviation, Table 2) regarding these criteria also emphasize their overall importance for this decision making, whereas the impact of expected risk-free project profitability on overall ranking needs to be considered with caution due to low consensus among panellists.

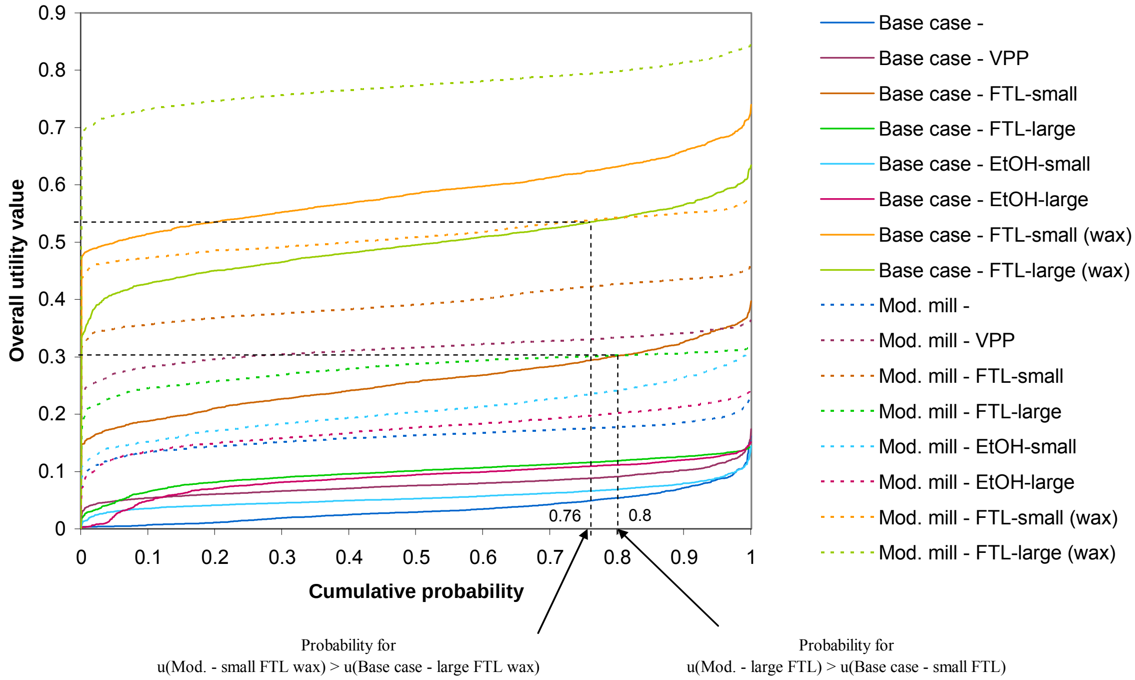

Figure 7. Results of the Monte-Carlo analysis of overall utilities' sensitivity on panellists' preferences

Based on the sensitivity analysis, the expected ranking is not changed due to the dispersion in opinion of the panellists. However, it is clearly seen that the alternatives where retrofit is done on the base case mill are more sensitive than alternatives with co-current mill modernization. For example, large FTL waxes process integrated into the base case mill -scenario is overlapping with the scenario of small FTL waxes process integrated into modernized mill. Thus, this information is useful when choosing between these two very similarly preferred alternatives.

Conclusions and implications

Compared to traditional approaches used in strategic investment decision making (one project performance measure, and a qualitative and subjective risk assessment) this systematic quantification of relevant financial performance factors and their importance shows great potential: better informed decisions can be made based on accurate and objective analysis of all scenarios. This is achieved through systematic assessment of the mill's capital spending history and future investment plans and integration cost-impacts resulting from process and business integration, using appropriate project and facility-level performance measures. The case example results can not be generalized to other mills or other capital spending scenarios (e.g. different products) but rather illustrate the application of this overall MCDM method and measures of identified performance factors in capital appropriation process.

Potential extension to the case study analysis considering only one mill is to expand the method to several mills of a company to differentiate mills from each other as hosts for specific biorefinery strategies, and further to distinguish between good and less good capital spending scenarios for each mill of the company. Moreover, the set of criteria now focuses only in financial performance and managing the uncertainties in external factors. It could be supplemented with analysis of other uncertainties. However, the pre-feasibility level design analysis required for this approach makes it imperative to pre-screen all possible scenarios using some criteria prior to this evaluation. As a result of this pre-screening, investment opportunities with similar level of technology and market maturity are obtained for more detailed decision making.

The case example results indicate how important the short-term criteria are for the decision makers at the case mill. This is partly result of the mill's situation (e.g. current products' demand and prices are high and feedstock availability and prices are stable). Among the short-term criteria, risk mitigation is of highest importance to the panel. Moreover, the ranking of considered strategic options for biofuels and bioproducts production show that FTL production with many configurations would be most promising alternative to bring further to feasibility level analyses.

Even though attractive as an alternative, mill modernization alone does not necessarily provide a good future for the mill; rather mill modernization combined with a biorefinery implementation might be a better solution.

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APPENDIX F – Book Chapter: Techno-Economic Assessment and Risk Analysis of Biorefinery Processes

Techno-Economic Assessment and Risk Analysis of Biorefinery Processes

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Abstract

Traditional techno-economic assessment and techno-economic risk analysis methods that are applicable and currently used in early stage biorefinery process design are reviewed: Key methods for capital and operating cost estimation, profitability analysis are discussed and suitable methods for incorporating uncertainties into these techno-economic analysis method steps are identified. Primarily focus is on early process design stage because of the current development level of many biorefinery processes, products and business models and because of the importance of design decisions at the early stages of design. Due to this aspect of biorefinery industry – the early development stage – several sources and forms of uncertainties

exist. Therefore, in this chapter an effort is made to consider aspect of guaranteeing commensurate techno-economic comparison between different biorefinery alternatives under uncertainty: the sources and formulation of the uncertainties are considered and linked with different process design assessment levels and the risk analysis aspects focus on the sources and quantification of uncertainties in techno-economic analysis implying measurable economic impacts. A particular biorefinery scenario of interest of many key players in biorefinery development, integrated forest biorefinery and the challenges related to techno-economic analysis are considered. Lastly some case studies are reviewed and a concretizing example is presented.

1 Introduction

Traditionally process design is defined to include process creation, synthesis, analysis, integration and optimization activities in a step-wise manner to arrive at an optimized solution for an engineering or societal problem that has at least satisfactory performance. In the early stages of the search for a solution and also in later steps of refining the designs, different methods are used, e.g. scenario-based creation of alternatives, or heuristics using screening of non-feasible options, or more systematic mathematical formulation of all possibilities and analysis and optimisation of the generated superstructure to find a set of most promising alternatives. Especially the approaches that are heuristics-based, such as the onion-method described by Smith [1] and the hierarchical process-flowsheet synthesis, development, evaluation and selection –method discussed by Peters et al. [2], are applied multiple times through the design process and integrated with other approaches. For example scenario development for process creation utilises heuristics that stem from engineering and other related perspectives of the same design task such as corporate and business planning. On the other hand, computationally heavy optimisation problems often are reduced by using heuristics.

Steps of traditional process design are illustrated in Figure 1.

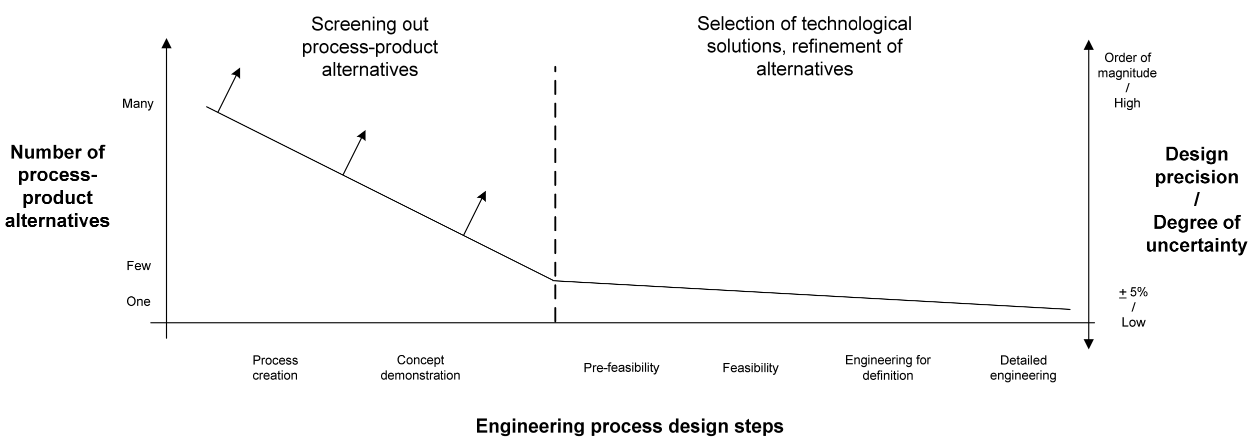


Figure 1. Process design process

In the early stages of process design low fidelity analysis methods are applied on a large number of process-product combinations and suitable decision making metrics are used to screen-out non-promising solutions. The methods used and the level of detail in information lead to low accuracy in the results of the analysis, moreover, especially in the case of analysing emerging technologies degree of uncertainty is high. Further on in the design process more advanced analysis is conducted on few most promising process-product alternatives to enhance the precision and lower the degree of uncertainties and in order to guarantee the selection of the best solution for the current demand.

The early stages of design process, creation of process alternatives and concept demonstration, are tightly linked with strategic planning and management of the facility and the company. Depending on the problem statement this linkage is also reflected in the selection of decision making criteria: in analysis of pure process development and improvement projects short term project related performance metrics are often most useful to estimate the return on invested capital, whereas for more strategic design projects, such as analysing the implementation of a new product-process combination or a large scale retrofit process, longer term performance measures combined with short term metrics might be more suitable. Strategic long-term performance measures are commonly used in corporate finance.

Biorefinery design process follows the principles of traditional chemical process design. Some particular features of biorefining however are in key role especially in the early stages of design and need further explanation.

Many of the products under investigation and development for the biorefinery, even though attractive and perhaps valuable, have uncertain prospects. These uncertainties arise from markets, for example the development time of the markets for higher value-added bio-chemical products or intermediates is unknown. Or, when it is possible to produce suitable quantities of these chemicals, how will the market react to the new bio-based product price-wise. On the other hand, lower value commodity products might not provide high enough revenues to justify the investment. Hence, the selection of products and their markets from the vast amount of possibilities is as such a complex decision to make. These decisions are normally done separately to process design activities, however the link between product and process development is critical and interaction and iteration between them is required for successful biorefinery implementation.

Another important specificity of biorefinery process design compared with traditional chemical process development, and also a significant source of uncertainty is the feedstock and its preparation: Biomass exists in various forms and possesses time-varying and sometimes unwanted properties, even though the main building blocks of all biomass are the same (cellulose and lignin). The processing of this raw material is also considered to be one of the most costly process steps. Also the supply of raw material is very different from the traditional chemical industries: point-like sources and piping is common in oil-based chemical industry, whereas biomass is spread on large, usually remote areas with relatively low yield per unit area. On the other hand the supply of similar biomass resource, wood, is currently well managed by forest industry. Third important factor related to feedstocks is the future dedicated biomass resources and their properties and cost as biorefinery raw material.

Third specificity of biorefining are the various processing pathways: biological processes, similar to the processes used in food manufacturing, are proposed to be utilised in many processing steps. Many of these biological processes, such as enzymatic hydrolysis and fermentation using yeasts or bacteria are very selective and currently established only for a few products. Because of the specificity, development of such processes for new applications such as production of value added chemicals is still undergoing, therefore only laboratory level information is available. Scaling up the idea to a commercial process introduces a new challenge and various uncertainties for the process design and analysis activities.

At industry-level, same properties can be used to describe biorefining and traditional chemical process industries: both are capital and energy intensive. This leads to substantial pressure to biorefining as financing large development and implementation projects of developing industrial sector is difficult. In order to secure financing, biorefinery integration into existing processes such as pulp and paper mills or petrochemical plants might provide some leverage: using centralized utility systems, existing raw material supply systems and knowledge and product distribution channels, as well as suitable mass and energy integration between existing and new processes can offer substantially lower capital investment requirement and cost of production. Integration of a biorefinery into existing business implies also modifications of the business model that in turn implies possibly a different company strategy and the need for analysing different strategic alternatives.

In summary, specific features of biorefinery both make the future prominent and uncertain. This poses challenges for process design and techno-economic evaluation especially in early stage design.

2 Techno-economic assessment

2.1 Overview of techno-economic analysis

Techno-economic analysis is normally requested by either company management when they are developing and modifying capital spending plans, or the R&D department when testing new ideas for implementation. Conventional capital appropriation process in corporate finance context, described for example by Northcott or Åberg, [3, 4] is a step-wise process: 1) Identification of potential investments; 2) Project definition and screening; 3) Analysis and acceptance; 4) Implementation; 5) Monitoring and post-audit. It is clear by comparing this appraisal process and the process design process (see Figure 1) that they have similarities: early stages of process design process correspond to steps 1 and 2, and detailed process design phases step 3 correspondingly in capital spending planning. This capital spending planning process is commonly utilised in both operational (short-term) and strategic (long-term) capital investment decision making. In the case of strategic decision making additional aspects are often also considered to account for company level performance changes and intangible implications of the strategic investments.

Techno-economic assessment is needed at all levels of process design process to provide the decision making information for the corresponding steps of investment decision making process or R&D decision points. It consists of several closely integrated parts: evaluating technical feasibility, capital costs, operating costs and revenues and finally estimating the profitability using a set of suitable measures of technical and economic profitability. The scope and objective of the techno-economic analysis are defined by the capital appropriation process or the R&D programme of a company. This sets the required level of detail and therefore also the needed steps in overall design process and the methods needed in techno-economic analysis.

Capital cost analysis is commonly in the main focus of engineering economic analysis literature and due to its importance it has well established classification based on the characteristics of different levels of the design process. For example Christensen and Dysert have reported best practices of capital cost estimation [5] using 5 classes of project definition. These classes correspond to the verbal classification used in Figure 1: class 5 is combined process creation and concept demonstration phases, other classes (4-1) correspond to the more detailed design phases. The skewed nominal range is a result of the level of detail of the design (lower level of detail leads often to underestimation of the total amount of required process equipment and therefore underestimated capital cost estimates).

No classification is however available for the two other factors of the cash flow, revenue and O&M cost estimation that will in the long term define the profitability of the business. These factors can be assumed to have similar behaviour as capital cost nominal range has because of the fact that more effort is made to evaluate them when less process-proruct alternatives are analysed. In Table 1 all aspects of techno-economic analysis, including also the classifications of cost analyses, are listed.

In early stages of process design mainly capacity-factored methods are used: capital costs are estimated based on total realised costs of existing installations and various factors and indices, such as scale-up factors, Chemical Engineering Plant Cost Index or the Marshall & Swift Equipment Cost Index. Capacity-factored method can also be applied on assembly-level or equipment level capital cost analysis. If substantial differences between reference data and the design exist and in later steps of design, equipment-factored methods can be used. This however requires more detailed reference and design data, for example equipment materials and process conditions and previous project execution information need to be known.

Operating and maintenance costs are also often calculated using factors: some fraction of capital costs or a specific cost structure derived from industry averages is assumed to represent the O&M costs of the new design instead of accounting for individual material flows and prices. These methods lead to substantial loss of accuracy, however, in order to be able to analyse a large amount of concepts in a short time simplifications are justified. Especially if the uncertainties arisen from the used method are systematically considered and all considered alternatives are analysed at the same level of detail, even the simple approach guarantees ***relatively correct*** results – which is also the goal of the analysis at this analysis phase.

Capacity and equipment-factored methods are simple parametric models where parameters are capacity or equipment specific parameters. More sophisticated parametric models can also be developed based on the analysis objective. The models should be developed from actual costs and knowledge of the process behaviour relative to the aspect that is modelled. These parametric models are very useful in early stages of design to be able to analyse in a short time many alternatives, however the task to develop reliable and relatively accurate models can be time consuming and data-intensive.

The most detailed cost estimation methods are based on actual prices of the equipment obtained from equipment manufacturers and system vendors. In addition to the equipment cost the total capital cost is based on case specific installation costs, labour rates and project schedules. Critical part of detailed cost estimation is to have correct level of detail design information of all aspects of the process: the cost result precision gained by detailed analysis of most of the process can be lost if one part or system is only factored in or not analysed at all.

When the scope of the design analysis is more detailed, O&M cost estimate accuracy also increases: The basis for O&M cost estimate, mass and energy balance with all flows, is better defined, labour requirement of all processes is established, cost of required licences and other annual fixed costs are estimated in more detail (operating materials, repairs, insurances, overheads) and facility location specific information is more precise.

Table 1. Characteristics of process design and techno-economic analysis [2, 5-9]

Design analysis characteristics				Techno-economic analysis characteristics				
Name	**Goal**	**Number of process-product combinations**	**Technology development scale required (entire process, not only parts of the process)**	**Analysis basis**	**Capital and O&M cost estimation method**	**Nominal range for capital cost estimate**	**Nominal range for O&M cost estimate**	**Profitability analysis methods**
Process creation	Systematic generation of alternatives/concepts Screening of non promising alternatives/concepts Defining production capacity	MANY (raw material-process-product combinations, capacity free)	laboratory - commercial	Input-output process mass and energy balance	Capacity factored, parametric models	Order of magniture	Order of magniture	Operating profit, capital cost, gross profit, technological maturity
Concept demonstra tion	Systematic generation of alternatives/concepts Screening of non promising alternatives/concepts Defining production capacity	MANY (raw material-process-product combinations, capacity free)	laboratory - commercial	Input-output process mass and energy balance	Capacity factored, parametric models	Order of magniture	Order of magniture	Operating profit, capital cost, gross profit, technological maturity
Pre-feasibility	Screening/selection of alternatives and production capacity	FEW (fixed product, process, feedstock, capacity)	pilot - commercial	List of main process equipment. Input-output process mass and energy balance	Equipment factored, parametric models	-30% - +50%	(+/-) 20%	ROI, IRR, NPV,

feasibility	Screening of internal process options and technological solutions	FEW (MANY internal alternatives for process departments, technological solutions)	Demonstration - commercial	Engineering & design data: main PFDs & equipment listing, detailed mass & energy balance	Equipment factored, parametric models	-20% - +30%	(+/-) 10%	ROI, IRR
Engineeri ng for definition	Budget authorization/cost control	FEW	Demonstration - commercial	Engineering & design data: PFDs, P&Ids, utility flow drawings, equipment data sheets, motor lists, electrical diagrams, piping isometrics, equipment and piping layout drawings, plot plans and engineering specifications	Semi-detailed unit-cost estimation with assembly-level line items	-15% - +20%	(+/-) 10%	ROI, IRR
Detailed engineerin g	Control of bid/tender	ONE	Demonstration - commercial	(same as above)	Detailed unit-cost estimation with detailed takeoff	-10% - +15%	(+/-) 10%	ROI, IRR

2.2 Techno-economics of biorefineries

Techno-economics of biorefinery processes are expected to be similar to petroleum based chemical industry's techno-economics: Lynd et al. compared historical development of corn wet milling based biorefinery industry and petroleum refining in USA and concluded that both industries have developed to low margin, diversified products producing and capital intensive industries that need to manage well multiple raw materials [10, 11]. Because of the long history it took get to this point, more than 150 years, more recent lignocellulosic biorefinery business concepts need some time to develop as far, but similar future characteristics can be expected.

The key techno-economic factors in petroleum-based as well as all biomass-based industries such as pulp and paper industry are feedstock, energy and capital costs and product portfolio. Same behaviour in biorefining can be seen based on public domain studies:

- More detailed biorefinery case studies than the industry level studies by Lynd et al., in the field of biofuel production, have shown the importance of feedstock cost for overall biorefinery process economics. For example corn stover based biochemical ethanol case study by Aden et al. considering relatively low feedstock cost of 30$ US/dry US ton found out that feedstock costs contribute 31% of total ethanol production costs (including capital charges corresponding to 10% capital recovery rate) [12]. Correspondingly, in thermochemical ethanol production case study using woody biomass as feedstock, even higher cost-contribution from feedstock was reported (43.7% of total production costs, 35$ US/dry US ton of biomass) by Phillips et al. [13].

  The cost of feedstock is probably going to change in future: competition from the same biomass is pulling the unit price up, whereas development in biomass growing, harvesting and processing can push the cost per unit of final product down. Feedstock cost is also very much location specific: competition of the same raw material, types of raw material, growing conditions etc. can vary locally. The process economics are therefore very sensitive to location and raw material assessment is a very important step of techno-economic assessment. Some unexpected solutions might become profitable under suitable raw material cost conditions.

- Many biorefinery technologies are energy intensive: Large amounts of heat are needed in pre-treatment and purification processes, or, achieving correct process conditions (pressure) requires high amount of electricity. Many technologies are designed for energy co-production: part of the feedstock is intentionally converted to steam and electricity to supply the process demand. This implies substantial additional capital investments in the energy systems and at the same time lower product yields.

- Typically biorefinery technologies imply relatively high capital investment costs.

  - Biochemical processes include lengthy, low consistency and complex biological steps such as hydrolysis or fermentation. The duration and complexity are further extended if more recalcitrant lignocellulosic feedstocks such as wood are used instead of sugar-based raw materials. These factors increase the size of equipment and therefore directly the capital cost requirement. Another costly step is the separation/purification step in biochemical processes due to the low consistency requirement of the biochemical processing steps.

- o Thermochemical processes often use such process conditions that require expensive materials to be used in process equipment. Process conditions are described by high temperature and pressure. Also depending on the type of thermal degradation process used, expensive oxygen separation and/or synthesis gas conditioning systems are required.

- Promising products from future biorefineries, other than and in addition to biofuels, have been studied extensively. For example Werpy et al. and Bozell et al. conducted comprehensive studies of most promising chemical products from biomass-based intermediates (sugars, synthesis gas or lignin) [14, 15]. This means that several potential solutions exist for diversified product portfolio, like it is the case with petroleum refining and partly for pulp & paper industry.

The techno-economic performance of a biorefinery, based on previous key cost and revenue factors, does not appear very attractive in general. This is also the current state of the pulp & paper industry and petrochemical industry, with some exceptions. However, both of the existing compared industries can possibly enhance the performance of biorefinery processes through integration of processes and businesses offering cost reduction, environmental benefits and improved operating margins.

For example, integrating the biorefinery process to an existing facility with suitable utility systems in place could offset capital costs. For example Hytönen and Stuart considered utility-integrated biofuel production scenarios where host facility was a Kraft pulp mill [16]. Naturally the existing systems have only some excess capacity available which in many cases might not be enough for even a small biorefinery. However, concurrent utility system capacity expansion with biorefinery implementation enables partial capital cost allocation to existing products lowering the capital cost requirement of biorefinery. In addition to the capital cost benefit, possibly higher biomass conversion efficiency to products could be achieved.

Other prominent cost lowering integration impacts include biomass supply using existing supply chains of forest industry or product sales and marketing through petrochemical companies' experience. These are accessible through correct implementation strategy.

Early stage techno-economic analysis of biorefinery processes often relies on publicly available information obtained from technology developers and the understanding and knowledge of the analyst. The goal of technology developers is often to attract funding for further development and demonstration of their new emerging technologies. Later on when the technologies are developed closer to commercialisation, more detailed data is not available for public. Because of this information availability and reliability it is important to critically analyse the emerging technologies in early stage design analysis.

Recognizing all above mentioned important characteristics of biorefinery technologies – key cost factors, integration possibilities, technological development stage, strategic nature of biorefinery projects and availability and reliability of process and product information – it is obvious that accounting for the uncertainties is required in order to be able to screen-out systematically non-promising alternatives in early stage design decision making.

3 Techno-economic analysis under uncertainty

In process design several sources of uncertainty exist. Pistikopoulos classified sources of uncertainty in design – a) model-inherent, b) process-inherent, c) external and d) discrete – based on their nature [17]. These uncertainties also try to capture the uncertainties existing at the outset of the design project, namely the uncertainties at company, industry or general environment levels. This division to three levels of uncertainties considered in management, listed by Miller and Waller [18], are normally called external uncertainties (category c in above list) in process design analysis. For example, at company level behavioural uncertainties related to management actions are normally not included in design analysis, whereas uncertainty in company debt and equity amounts and required rates of return are commonly accounted for.

General risk analysis follows four main steps: 1) Identification of sources of uncertainty, 2) quantification of uncertainties, 3) formulation of uncertainty for risk analysis, and 4) quantification of risk. In techno-economic analysis the risk analysis method should be selected depending on the process design stage (the goal of the design analysis), the sources of uncertainty and information availability. Several methods for incorporating uncertainty into techno-economic analysis exist; all of them can be classified to be either qualitative or quantitative methods.

The following sections describe the different methods that are used in early stage process design context and show their applicability for biorefinery design.

3.1 Qualitative analysis methods

Qualitative risk analysis is best suited for investment strategy or project risk evaluation and it can be considered to be a prerequisite for any process design activities and more detailed quantitative risk analysis. Example of qualitative risk analysis methods is SWOT analysis (project Strengths, Weaknesses, Opportunities, and Threats -evaluation) that is commonly used in strategic planning and in capital spending planning. It subjectively "quantifies" verbally each uncertain aspect under generic, qualitative conditions to arrive at overall benefit-disadvantage description of each considered scenario.

3.2 Quantitative analysis methods

Quantitative risk analysis uses, instead of verbal "quantification" of the system's behaviour, different numeric scales to categorize the input parameters or the system's behaviour under certain conditions. It can be further divided into deterministic and stochastic methods. More detailed description of these two classes and main analysis methods used in process design is given in sections 3.2.1 and 3.2.2.

Optimisation under uncertainty is a wide class of approaches incorporating deterministic or stochastic analysis into mathematical programming based design and operations analysis. A substantial body of knowledge has been developed during the past decades in both stochastic based approaches (see [19] for a recent review) and deterministic based approaches, main features of these methods relative to early stage process design risk analysis are also given in section 3.2.3. No attempt is done to cover optimisation and different optimisation methods; focus is on incorporation of uncertainty in mathematical programming and the usefulness of these methods for early stage process design techno-economic analysis.

3.2.1 Deterministic analysis methods

Deterministic risk analysis includes two types of methods: I) methods where the uncertain input parameters can only be given a range of possible values, all values inside the range having the same probability of occurrence. Second characteristic is that the quantified uncertainties can be propagated through the analysis model to end results; II) methods where some aspect of the system is considered uncertain and it can be categorized subjectively using an ordinal or verbal scale and be represented as a result. Normally the methods either arbitrarily or based on knowledge of the context and heuristics of the phenomena behind the uncertain parameters quantify the uncertainty and fix the parameters to some values to form a set of scenarios for analysis.

Type I methods:

- The simplest deterministic method to evaluate the impact of uncertainty is interval analysis or sensitivity analysis. In this approach ranges (minimum and maximum values) are used for uncertain model parameters, this is especially useful if no information of likelihood or probability of parameter values is available. By solving the problem with boundary values of all uncertain model parameters the absolutely worst/best case scenario is modelled, however, no indication of the likelihood of the modelled outcomes is achieved [20]. In process design sensitivity analysis, instead of focusing only on the worst/best case scenarios, uncertain parameters are considered one at a time keeping other parameters in their expected values (base case values). This gives the sensitivity of the system to the parameter in question. This analysis is especially useful in identifying the risky system parameters: parameters that have substantial impact on the analysis results if they vary over their quantified range of values.
- Another deterministic method called scenario planning or analysis uses the same principles as interval analysis. Schoemaker describes scenario planning as: By iterative and interactive group decision process, including discussions among managers and other stakeholders, all different likely future scenarios, thus the likely values of risky parameters, will be examined leading to few most plausible and internally consistent future scenarios [21]. Even though this scenario planning method is intended for strategic planning level, it also captures the main idea of risk mitigation and analysis in process design. Scenario analysis approach is often used in process design to generate input value scenarios, however the formal process of defining the scenarios proposed by Schoemaker is not followed in early stage design due to the demands of the planning procedure (time and resources are not always available). More “streamlined” version is used instead: a group of experts of the field, such as the process design group including main personnel from existing operations if retrofit design problem is in question, selects the scenarios to be analysed. This approach has the same weakness as interval analysis – the probability of planned scenarios is not achieved systematically.

Type II methods:

- One form of scenario analysis or sensitivity analysis are different scoring methods: Subjective understanding and knowledge of the analysed system is used to quantify the magnitude of the uncertainty in some behaviour of the system instead of using some formal method for converting the quantified input uncertainties into the uncertainty in outcomes using the techno-economic model. It uses some ordinal scale for quantification of the uncertainty. The uncertainty can be either in the same performance measures as are used as final result of the analysis (see below description of discounting methods) or in an additional system behaviour. In the latter case new metrics are required for decision making process. Scoring methods can be useful in multi-criteria decision making in early stage design in order to avoid complex models and time consuming modelling and simulation.

- Discounting methods are a variation of scoring methods that are very close to qualitative risk analysis methods. By using an ordinal or verbal scale, the results are discounted case specifically in order to be able to better compare different scenarios or process design alternatives. For example, if it is known that the main product of a design alternative has established markets, no discounting of profitability of the process alternative is done. On the other hand, if the main product does not have existing markets, or the market is difficult to enter, the profitability of that design alternative is discounted based on developed scale. Hence, instead of changing the price of the final product, the perception of the market conditions is used to evaluate the impact on profitability. Similarly other design aspects can be addressed, such as technological maturity or design data reliability.

3.2.2 Stochastic analysis methods

Stochastic risk analysis is based on the idea of giving a probability distribution to each uncertain model parameter. Selecting randomly values from these distributions, a large amount of scenarios (input parameter combinations = scenarios) is formed. In the analysis of all these scenarios all uncertainties are propagated to the end results forming their probability distributions, e.g. the probability distribution of profitability of the investment project. One important feature of stochastic analysis is the correlation of uncertain parameters: strong correlation between two or more uncertain model parameters, for example oil and gasoline prices (examples of input and output of a chemical process), enables simpler model since only one distribution is required to describe the behaviour of all strongly correlated parameters. On the other hand, if the correlations are not identified, unrealistic random parameter combinations will be included in the analysis and these can distort the outcome distribution.

Most well known stochastic analysis method is Monte-Carlo (MC) analysis. All uncertain model parameters have probability distributions; the solver randomly selects values from the distributions and calculates the outcome. By repeating this several times (often 10^5-10^7 times) many of the possible parameter combinations (scenarios) are calculated. Because the randomly selected input values are based on their probability the result is correctly distributed.

As it is obvious from above, this method is simple but requires a lot of computation time. This, often also called as brute force, method of random sampling can also be enhanced by other sampling methods. Often compared methods are the Monte Carlo Sampling (MCS) and Latin Hypercube Sampling (LHS), see for example Diwekar and Kalagnanam or Wang et al. [22]. In LHS the probability distributions are divided into equally probable intervals and, for example, the average value of each interval is used as input value. All distributions are treated this way and the average values are organized to a matrix which is used as an input to the MC function. This “stratification” of distributions leads to faster computation and reduces variance.

Other sampling methods have also been developed for better representation of the distributions and decreased computation time. Wang et al. show the efficiency of combined Latin hypecube-Hammersley sequence sampling in several different cases and it is clear that this combination is much better sampling method than the MCS and LHS [22]. The mathematical formulation is however often more complex formulation than MCS and LHS and therefore application into real problems is not common.

The interpretation of the results of stochastic modelling involves always two aspects, the expected value and the variance or statistical dispersion. By presenting the result distribution as Cumulative Distribution Functions (CDF) these two aspects are easily combined and mathematical methods for comparing CDFs of considered options exist. Graves and Ringuest compared 6 methods for comparing uncertain alternatives. They propose two, almost stochastic dominance and mean-Gini methods, to be most suitable for comparing several options [23]. However, if multiple criteria are considered in decision making instead of only one theoretical models for comparison are not available; uncertainty of the criteria needs to be in these cases considered as another criteria or as additional information for subjective decisions.

Another method for estimating the the uncertainty in outcomes is based on the definition of variance: variance is the second central moment of real valued random variable which can be estimated using a Taylor expansion of the function describing the outcome y as a function of its variables x, $y = f(x)$. The expansion is often truncated after the second order terms and in the case of non-correlated variables x, the covariance between variables can be omitted leading to less complex formula for the outcome variance. This method, called law of propagation of error (LPE), is commonly used in analysis of the impacts of measurement uncetainty on results reported with a metric calculated from the measurements (e.g. variance of resistance is calculated from measured voltage and electric current). It is not however commonly applied to process design context.

Xiao and Vien compared this method with Monte-Carlo analysis in mineral processing system modelling and concluded that even though LPE can be applied in this context, Monte-Carlo analysis leads to more informative and accurate results. The main reason is that LPE is only able to give correct answers for linear functions, whereas Monte-Carlo analysis can also handle non-linear and complex system models. [24]

The limitations of this LPE method (inaccuracy when complex, non-linear systems are analysed) in process design context can be however justified in cases where calculation time is an important factor: by evaluating the single one equation is fast compared to 10^5-10^7 iterations often conducted in Monte-Carlo analysis. Also, if the actual propability density function is not the objective of the uncertainty analysis and the statistical moment (variance or standard deviation calculated from variance) of the outcome is sufficient, LPE could be applied in process design risk analysis.

3.2.3 Optimisation-based analysis methods

Optimisation under uncertainty is a vast and quickly expanding group of methods applicable to process design analysis at all design stages. Depending on the goal of the design analysis and the information availability the formulation of uncertainty is selected. This also defines the optimisation methods that can be used.

Optimisation based methods using finite number bounds or fixed parameter values, hence scenarios, to describe the uncertainties are deterministic approximations of the system and optimisation of these scenarios is called deterministic optimisation under uncertainty. These possible model parameter combinations (scenarios) can also be given a probability value for example using expert opinions. This probability of the occurrence of the scenarios is then also the probability of the corresponding result. Another type of deterministic optimisation under uncertainty is to conduct sensitivity analysis with a deterministic optimization model.

In stochastic programming the uncertain model parameters can be selected either randomly from their probability distribution or based on the knowledge of the analysts (called deterministic stochastic programming). The resulting uncertainty in decision variables is then solved using different methods [19]:

- Recourse-based stochastic optimisation:

  Classical recourse programming divides the decision variables into two stages. The first stage variables are fixed under some particular realization of the uncertain model parameters to see the actual realization of the uncertainty in the uncertain second stage variables, called also the recourse variables. These recourse variables represent the cost of corrective measures against the infeasibility of the solution, and as they are the result of random parameter realization, the cost is random as well. The objective is to minimize the total cost (the sum of the expected first stage cost and the random second stage corrective cost). If parameter probability distributions are discrete, the optimisation problem can be solved using linear programming and actually the problem reduces to a scenario tree of parameter realizations. In the case of more generic distributions, sampling-based schemes can be used to solve the optimisation problem.

  Methods based on this classical recourse-based method are: stochastic linear programming, stochastic integer programming, stochastic non-linear programming and robust stochastic programming. They differ from the classical method in the types of variables that can be included (linear vs. non-linear, continuous vs. integer/binary), in the formulation of the objective function and in the interpretation of the results. For example robust stochastic programming includes a variability of recourse variables -term in the objective function to reflect the different preferences of decision maker. Compared with other stochastic recourse-based methods this enables the modelling of risk adversity instead of risk neutrality that is the basis of the other methods.

  In general, all recourse-based methods aim to minimize the cost of infeasibility, hence they allow infeasible solutions with a penalty or a cost.

- Probabilistic programming approaches the problem from another perspective: it focuses on finding solutions that are best able to meet the feasibility requirements under uncertain conditions.

- Fuzzy mathematical programming uses fuzzy numbers and fuzzy sets to describe uncertain model parameters and constraints. Membership functions are used to describe the constraint violation, hence the uncertainty in the constraints. They also describe the degree of satisfaction of the constraints and the uncertainty range of coefficients of objective function.

- Stochastic dynamic programming adds the dynamics of uncertainty into stochastic programming. Discrete-time systems can be solved using above described stochastic programming methods in a recursive manner by solving all tail sub-problems and using these solutions to solve the major problem.

Algorithms and methods applying above mentioned and other methods have been developed in Process Systems Engineering (PSE) community for chemical process design and synthesis purposes. All above described methods are applicable to early stage design aiming at screening based on techno-economic performance and uncertainty of the considered alternatives. The decisive factor in selecting the method is the goal of the design activity because of the different capabilities of the methods. Mostly applied in design context are stochastic programming methods (see for example [25, 26]).

In recent publications Svensson et al. describe a deterministic stochastic optimisation method for early stage retrofit design problems and demonstrate the method with pulp mill retrofit investment project identification problem. After identification of minimum amount of non-correlated uncertain model parameters (only prices and CO_2 emission charges considered), parameter sets are defined. These parameter sets are given a probability and a validity period. Combining these sets to form future paths and giving a probability to each path the possible 25 years long time scenarios can be modelled. The problem is solved using multi-stage mixed-binary linear programming method, objective function was the maximization of expected net present value and the first stage variables were the initial investments that were needed to define the outcome of uncertain parameters. This combination of parameter uncertainty and time dependency of decision making leads in the case study analysis to a robust and surprising investment solution and proves the importance of uncertainty and time considerations in strategic investment decision making. [27, 28]

3.3 Critical aspects of early design stage uncertainty analysis

A generic challenge to all methods is the second main step, quantification of the uncertainties, to be able to objectively represent the prevailing uncertainties. Especially critical this is in the early phases of process design where in general less information is available and less accurate methods in design analysis are used. When using any of the discussed risk analysis methods the user should try to address this challenge, however the way of addressing differs between the methods since the formulation is different.

Hubbard and Evans consider the possible problems of scoring methods which often rely on ordinal verbal scales [29, 30]. The human aspect of risk analysis – different perception and setting of the severity of each risk factor, and the perception of the scales in use – can bring an additional uncertainty to the risk analysis results. Also, invisible correlations between uncertain parameters can create false outcomes in scoring method analyses. Hubbard and Evans conclude that when recognized and carefully considered these problems can be avoided. Another option, based on their analysis, is to use stochastic methods.

On the other hand, using stochastic methods can also be considered to be subjective and sometimes lack the decision makers' understanding of the underlying phenomena (origins of uncertainty) and therefore the probability distributions are only perceptions of the real distributions. Bode et al. discuss the need to better assess the uncertainties in order to be able to reduce them for decision making in process design context [31].

It is also important to realize if an uncertainty is really an unknown factor that can only be estimated with time. These types of uncertainties might not be possible to be included in the analysis but they can still be managed. One example of this uncertainty-type is the future products: some properties can make a product very attractive but since no markets exist no-one will make an effort to develop the process for the production. However, with a strategy to make an enabling step towards production of that specific product might give an advantage in future, hence, the risk making the wrong product decision by rushing into unknown is reduced and managed by taking a step towards the new product and producing perhaps some intermediate product until the market is developed the investment can be justified. Another example of uncertainty unknown now but revealed in future are political decisions that have implications in technology development speed, market creation and prices and costs.

In conclusion, it is critical to always evaluate the types of uncertainties that are to be included in the risk analysis in order to decide whether to address them through the risk management strategy of the company or in the actual risk analysis step of the techno-economic analysis. In addition, the understanding of the subjectivity of the uncertainty and its formulation are important for a reliable and systematic risk analysis.

Second set of critical aspects are related to optimization based risk analysis methods: selection of the formulation of uncertainties and the risk analysis method. Many of the methods are computationally demanding. Therefore in early stages of design simplifiedmethods are most applicable to be able to analyse a large amount of design alternatives in a short time. Thus, deterministic optimisation methods and deterministic stochastic programming methods might be preferable.

When using optimisation approaches it is important to understand the type of uncertainty: if information is missing, fuzzy programming can provide methods for accounting for this better than stochastic programming approaches, on the other hand if probability distributions can be formulated, stochastic programming methods are more suitable.

3.4 Sources of uncertainty in design of the biorefinery

Many of the promising new biorefinery technologies are still at laboratory or pilot scale development phase, some biofuel technologies are the only exceptions being already at demonstration scale. Higher process-inherent uncertainties are evident for these new emerging process technologies compared to more developed processes: Many of the key aspects have not yet been addressed or even identified in an overall system like the final commercial process will be. Therefore the design data is not very reliable and seldom even available. Important process related uncertainties are for example the conversion efficiency of biological processes, the recycling of chemicals and bio-chemicals at large scale production or scaling up purification and separation systems to these scales of production. Because of this nature of the information often formulations of uncertainty neglecting the probability of uncertain parameter values can best represent the process-inherent uncertainties in early stages of design.

Equally important challenge is the understanding and quantification of the external uncertainties. Biomass markets and competition are developing and substantial changes in prices can take place in near future; Prices of many products (substitute or replacement for petrochemical-based products) are volatile and market size can only be forecasted; and project financing depends on both company level and financial market conditions. Due to the many unknown factors of the uncertain external parameters the risk management strategy becomes an important tool to account for them. For example, a lot of market information and understanding is available already for many commodity products (biofuels) but not for many value-added bio-chemical products and intermediate building block products. Therefore it is possible to consider external uncertainties of biofuel production scenarios systematically in techno-economic analysis but it is not necessarily possible for non-existing product scenarios. When more information becomes available for proper formulation of the uncertainties (with or without probability distributions) the analysis can be conducted. Until that, the uncertainty in value-added product scenarios can be considered through proper risk management and implementation strategy.

At every stage of design analysis the models that are used generate additional uncertainty:

- At process creation level when simple and often linear process and cost models are utilised the results are as reliable as the factors can represent the aspect in question. This applies to both traditional techno-economic analysis and optimization based superstructure analysis. For example, when estimating total capital investment cost of a new biorefinery process technology using realised investment costs of an existing facility of another product as reference cost, the capacity factor and other factors describing the differences between reference and new technologies are by definition averaged values. These factors can make the total capital cost estimates biased. Also, many external economic factors are excluded from the analysis at this stage adding uncertainty to the final profitability.
- In concept demonstration stage, the available design data is more complete and more detailed estimation routines are normally used. Hence, the data availability enables the use of better models to lower the degree of uncertainty arising from the process and economic models. At this level external factors related to financing and micro and macro economics are also more often modelled. This leads to additional uncertainty in the models that are used. For example, using net present value methods to model the profitability have well known shortfalls when comparing projects of certain properties (see for example corporate finance handbook by Ehrhardt and Ehrhardt for detailed discussion [32]). Internal rate of return (IRR) as performance measure for mutually exclusive projects with substantially different capital investment costs possibly leading to different capital structures and with different lifetimes – which can easily be the case in the biorefinery context, e.g. large biofuels plant versus processing of an existing side-stream to a low volume added-value product – can give contradictory results with the analysis of the same concepts using net present value (NPV) as the profitability measure. This model-inherent uncertainty can also be managed by selecting the models that best suit to the particular design project and by using multi-criteria decision making.

Discrete uncertainties in the early stages of biorefinery process design originate mainly from the technology and financing availability or political decisions, these aspects are often considered as given fixed values or they are included as pre-screening criteria:

- If a step of the process under analysis is not developed to the same level as the rest of the process, and the future development of it is not pursued by any equipment manufacturer or technology provider, the entire process might be screened out from the analysis that is being conducted, however not forgetting this solution from future analyses.

- If a company commissioning the design analysis has strict capital investment limits the availability of financing might be used as a fixed value pre-screening metric.
- If a particular bio-based product is a national or global priority, governmental funding for advancing technologies and developing the markets is often available. Other types of subsidies are product price and feedstock cost regulations. An important feature of all subsidies is that they are available for a pre-defined period of time. This type of discrete uncertainty, unknown existence, magnitude and duration (and impacting all other sources of uncertainty: external, process-inherent, model-inherent), is often considered through fixed scenarios.

The origins of uncertainty and suitable methods for including them in techno-economic analysis (resulting from the formulation of uncertainty) in biorefinery design context are listed in Table 2. The overall approach where these analysis methods are applied can be optimisation based or traditional techno-economic analysis method.

Table 2. Sources of uncertainty and suitable analysis methods classified by the type of uncertainty in early stages of process design techno-economic analysis

		Model-inherent	Process-inherent	External	Discrete
Process creation	Examples of uncertainty sources	Cost estimation models M&E balance dependencies	Product yields Energy consumption Equipment cost Process development scale	Raw material cost Product prices Market demand	Availability of overall process technology Availability of financing Availability of subsidies
	Analysis method	Scenario analysis Sensitivity analysis Scoring methods			
Concept demonstration	Examples of uncertainty sources	Cost estimation models	Process integration impacts Cost of all required equipment Consumption of all raw materials	Feedstock price Product prices Forecasts of prices	Availability of technological solution and equipment for specific process steps Magnitude and duration of subsidies
	Analysis method	Discounting methods	Scenario analysis Sensitivity analysis Stochastic analysis		Scenario analysis

The main sources of uncertainty given in Table 2 can be formulated for many analysis methods. The methods that are listed are selected based on the nature of the uncertainties and the objective of the design step: in process creation phase often many process design alternatives producing several different products are considered. Gathering and forecasting required market data (prices and demands of all products) for probability distributions can therefore be too time consuming task even if information were available and simpler methods to formulate the uncertainty is needed. A range of possible values is easier to establish and therefore if might be most suitable formulation type for considering external uncertainties. On the other hand in concept demonstration phase when less process design alternatives and also less products are considered a more comprehensive market analysis can be conducted in order to have distribution-type uncertainty formulation.

Similarly for process inherent uncertainties: after process creation and first screening the concepts that are left for consideration are more constrained (feedstock options might be narrowed to only few, or technologies for particular process steps are selected leading to more detailed process parameter information). However, enough process and design data might not still be available for distribution development and range-type uncertainty formulation is needed.

In further steps of process design process many of the key uncertainties analysed in early stage design analysis are reduced to substantial lower level and scenario or sensitivity analysis are often sufficient as risk analysis. For example process parameter variation (process inherent uncertainty) is narrowed to more tractable form because of excessive laboratory research or piloting or, due to more detailed process layouts and plans the capital costs can be estimated based on actual vendor quotes and previous projects leading to very low model-inherent capital cost uncertainty.

A group of uncertainties specific to a particular biorefinery business concept, integrated biorefinery, is the uncertainty in the integration impacts: in an integrated biorefinery, existing facility (e.g. pulp and paper mill, petrochemical plant or corn ethanol plant) and its systems and knowledge are utilised to run both the new and existing operations. To be able to benefit from integration, integration is needed at several levels from process to corporate business. The impacts of this biorefinery strategy are various, for example

- using same heat and power systems changes the overall energy balance and that has impacts on the operations of the existing production systems and therefore the production costs of the existing products
- if existing labour force is used to operate both processes, this lowers the labour costs of existing products and also changes the facility overhead charges
- Using the same raw material purchasing and product sales and marketing have similarly impacts on production costs of existing products.

However, no experience of such integration exists in many cases and the degree of integration at the different possible levels of integration is somewhat uncertain. Quantification and formulation of these uncertainties at process creation and concept demonstration level design analyses can in many cases only be done using ranges of possible impact degrees, thus leading to sensitivity or scenario analysis as suitable risk analysis methods.

4 Selected early design stage biorefinery techno-economic studies

4.1 Biorefinery case studies

The methods listed in Table 2 have been implemented in many types of early stage design and techno-economic analyses of biorefineries. Table 3 lists some of these case studies focusing on different characteristics of the studies. The characteristics that are analysed include the level of the design analysis, the main goal of the study, the initial and resulting amounts of design alternatives that were studied, the methods that were used in both capital and O&M cost calculation, different uncertainties that were considered in uncertainty analysis, the uncertainty analysis methods and the criteria that was used in screening or comparison of the design alternatives. Actual results of the studies are not reviewed.

Three selected case examples are reviewed in more detail in section 4.2 and one of the studies is further discussed as a concretizing example of biorefinery techno-economic and risk analyses in section 4.3.

Table 3. State-of-the-art biorefinery process design studies and their characteristics

Design phase	Goal of the case study	**Alternatives (in → out)**	Capital and O&M cost estimation method	Considered uncertainties	Uncertainty analysis method	Decision making or comparison criteria Decision making method *	Ref.
Process creation	State-level roadmap development (resource-product chain screening)	650 → 8	-	Qualitative External Process-inherent	PEST (Political/legal, Economic, Social, Technological) *Process* - SWOT	Survey score Feedstock flexibility *Method:* Step-wise MCDM (Multi-criteria decision making using qualitative survey results)	[33]
	Identification and weighting of pertinent pathway screening criteria for integrated forest biorefinery using biofuel processes as example design alternatives	7 → 7	Capacity factored method	Technological maturity	Scoring	techno-economic, environmental, feedstock flexibility, product diversification and energy and integration *Method:* Trade-off MCDM	[34]
	Demonstration of novel optimisation based design methodology using agricultural waste stream for fuel and energy generation	3 → 1	Capacity factored method	-	-	Profit *Method:* Optimisation	[35]
	Evaluation of alternatives for substitution of transportation fuels beyond 2010 in Europe	22 → 3	Literature values	MCDM criteria weights	Sensitivity analysis	Incremental cost of fuel substitution Total cycle GHG (green house gas) emissions Energy consumption Substitution potential *Method:* AHP (analytical hierarchy process)	[36]

Concept demonstration	**Comparison of close-to-commercial gas-to-liquids design alternatives with traditional Tomlinson recovery boiler retrofit**	**9 → 9**	***Capital costs*: Equipment-factored model** ***O&M costs*: capacity-factored model**	**Energy costs** **Feedstock cost** **Product prices** **Monetized environmental benefits**	**Scenario analysis** **Sensitivity analysis**	**IRR of Incremental Capital Investment** **NPV**	**[37]**
	Economic comparison of leading pre-treatment technologies for ethanol production from corn stover	5 → 5	Equipment-factored model	Ethanol yield with/without oligomer credit Solvent loading to pre-treatment	Scenario analysis	MESP (Minimum ethanol selling price)	[38]
	Compare the economics of five pre-treatment options and 3 down-stream processing options for ethanol production from corn stover	7 → 7	Capacity factored method	Pre-treatment and saccharification conditions and conversion rates Economic assumptions	Scenario analysis Sensitivity analysis	Product value	[39]
	Comparison of biofuel production pathways Identification of future focus areas in R&D of studied pathways	14 → 14	Equipment-factored model	Energy costs Feedstock cost Capital structure	Scenario analysis Sensitivity analysis	IRR Minimum selling price Total capital cost	[40-42]
	Techno-economic analysis of forest biorefinery concept based on near-neutral hemicellulose pre-extraction	1 → 1	Capacity factored parametric model	Pulp mill production capacity Availability of excess capacity and equipment	Scenario analysis	Ethanol and acetic acid production cost After-tax IRR	[43, 44]

Concept demonstration	**Techno-economic analysis of forest biorefinery concept based on acidic hemicellulose pre-extraction**	**1 → 1**	**Capacity factored method**	**Hemicellulose extraction rate** **Rate of cellulose degradation in kraft pulping**	**Scenario analysis**	**Production costs** **Capital investment cost**	**[45]**
	Demonstration of strategy to repurpose kraft pulp mill into ethanol plant	3 → 3	Capacity factored method	Ethanol revenue Capital cost Enzyme cost Biomass cost	Scenario analysis Sensitivity analysis	IRR Cash cost of ethanol production Total cost	[46]
	Screening of retrofit biorefinery implementation scenarios producing biofuels	42 → 6	Capacity factored parametric model	Biofuel production capacity Raw material costs Product prices Energy costs	Sensitivity analysis Monte-Carlo analysis	IRR Downside IRR Total capital cost *Method:* Single criterion comparison	[47]
Concept demonstration/pre-feasibility	Process design and economic analysis of corn stover based biochemical ethanol production process under investigation at NREL	1 → 1	*Capital costs*: Detailed cost estimates *O&M costs*: Equipment-factored model	Hurdle-IRR Equity fraction of financing Feedstock composition, cost and handling Yields Enzyme loading Energy cost	Scenario analysis Sensitivity analysis Monte-Carlo analysis	MESP	[12]

Concept demonstration/pre-feasibility	**Process design and economic analysis of poplar based biochemical ethanol production process under investigation at NREL**	**1 → 1**	***Capital costs*: Detailed cost estimates** ***O&M costs*: Equipment-factored model**	**Feedstock cost** **Hydrolysis and fermentation yield** **Capital cost**	**Scenario analysis**	**Ethanol production costs**	**[48]**
	Process design and economic analysis of corn stover based thermochemical ethanol production process under investigation at NREL	1 → 1	*Capital costs*: Detailed cost estimates *O&M costs*: Equipment-factored model	Hurdle-IRR Financing structure Feedstock properties Plant capacity Process step efficiencies By-product credit	Scenario analysis Sensitivity analysis	Fuel yield MESP	[13, 49]
	Demonstrate the benefits of using risk analysis in techno-economic analysis over traditional approaches in corn ethanol process design context	1 → 1	Capacity factored method	Product and by-product prices Feedstock cost Energy cost Operating interest rate Inflation rate	Scenario analysis Monte-Carlo analysis	PVENW (present value of ending net worth) NPV ROI (Return on investment) Variable production costs Probability of economic success	[50]

* If actual screening/selection is done, method is listed

4.2 Some selected studies in more detail

Three recent studies also listed in Table 3 are reviewed in more detail to give a better description of how key aspects of techno-economic analysis and risk analysis in early stage process design have been addressed. These aspects are the formulation of uncertainties and the method of risk analysis, study assumptions and cost analysis method.

Cohen et al. used scoring method to formulate one type of uncertainty, process inherent uncertainty, in process creation stage process design analysis [34]. Emerging technologies for ethanol production in an integrated forest biorefinery were analysed using multi-criteria decision making (MCDM) approach. Uncertain technical maturity or level of development scale of different processing steps of ethanol production processes was considered by assessing each processing step and giving it a subjective maturity score (value between 1 and 5). Normalized sum of the technology specific scores was used as one decision making criterion among other criteria (including techno-economic, environmental impact, feedstock flexibility, product diversification and energy integration impact criteria). This risk criterion was weighted by the MCDM panel and given a substantial importance as a decision making criterion in very early stages of process design.

The economic analysis in this study was a simplified capacity factored estimation of both capital costs and O&M costs under two conditions, current development of technologies and estimated future efficiencies and product yields. The profitability of each considered design alternative measured as return on investment (ROI) under these two conditions were used as separate decision making variables; the estimated future ROI was given the highest importance by the MCDM panel among all used criteria. This indicates that from the two very different sets of assumptions (current efficiency of processes and future estimated efficiency) the future process performance would be preferred basis for economic evaluation rather than current performance.

Kazi et al. studied several bioethanol production process design alternatives using corn stover as feedstock [39]. They used published process information instead of future performance estimation as the basis for all cost analysis: Capital costs were *n*th plant base case estimates corrected with a factor based on regression modelling of 44 processing plants (pioneering plant analysis). This factor accounts for the uncertainty in capital cost estimate (level of design definition, e.g. process equipment not demonstrated commercially, or impurity build-up). Correspondingly the production shortfalls during the start-up period were estimated using regression model. This factor accounts the impacts of the development scale of the process and the complexity of the process on the revenue during the first years of production.

In addition to these two regression analysis based factors, investment cost contingency was increased to account in general for the uncertainty of estimating the *n*th plant capital costs.

Using scenario analysis the impacts of uncertain process parameters (specific to each studied process design) on the main analysis criterion, product value, was estimated. These uncertain parameter values were taken from open literature and scenarios were constructed using minimum and maximum values found. The product value at the boundary values was compared to base case product value. The generic economic assumptions and overall process parameters were assessed separately as sensitivity analysis.

Second example of recent concept demonstration level design analysis is the work developed by Laser et al. [40-42]. They established a comprehensive comparison of different biofuel and energy co-production process design scenarios (including also biofuels as co-products). Capital costs were estimates using main equipment level capacity factored method based on literature cost estimates. O&M costs were estimated using the developed mass and energy balances (detailed simulation models) for raw material and energy consumption information. Literature based values for fixed operating cost estimates and prices (escalated to analysis year) were used.

All design scenarios were assumed to be mature technologically, hence the used process parameters were assumed to represent such processes that only incremental improvement in costs and benefits could be achieved with additional R&D efforts. The feedstock to all processes was switchgrass.

External uncertainties were considered using sensitivity analysis: prices of feedstock, electricity and oil were varied and IRR of the designs was evaluated.

The resulting economic performance of the considered processes was aggregated based on product mix to groups of design alternatives (bioethanol + co products, thermochemical fuels and power, power) to be able to make generic conclusions and compare different biofuel production strategies.

4.3 Concretizing example

Hytönen and Stuart analysed 42 different integrated forest biorefinery design alternatives (production capacity as free variable) in a concept demonstration level design analysis [47]. The following sections describe the context and the risk analysis steps focusing on the uncertainty formulation and risk analysis result interpretations of the study.

4.3.1 Context & techno-economic analysis method

A North-American hardwood kraft pulp mill was considered as host process of an integrated forest biorefinery consisting of different types of biofuels producing biorefinery concepts. Real mill information was used as analysis basis: Various feedstock options in the case mill location were considered: pulpwood, woody forest based biomass, corn grains, corn stover, food processing wastes as well as pulp mill side streams (black liquor and pre-extracted hemicelluloses); current and possible future pulp mill process configurations with specific system capacities were analysed. In addition, feedstock capacity was not constrained to one single value; rather a promising production capacity and therefore most promising feedstock capacity was examined during the study.

A detailed list of design scenarios and all economic assumptions can be found in the references. The main definitions are given below:

- Biofuel options in the study included bioethanol, Fischer-Tropsch liquids and mixed alcohols (including ethanol).
- Fuels and acetic acid (from one design alternative) were considered as by-product or co-product.
- Assessed process designs included both biochemical and thermochemical alternatives: biochemical processes used either enzymatic or acidic hydrolysis followed by fermentation

and distillation to produce ethanol and thermochemical processes used either high temperature gasification or steam reforming combined with fuel synthesis or syngas fermentation to produce FTL or mixed alcohols from which ethanol could be separated.

Design information for a base case design of each process was gathered from open literature. These all reference studies had assumed an *n*th plant design with future estimated performance, thus, more optimistic future process designs were assessed in this study as well. The base case designs were used to design other feedstocks processing alternatives based on feedstock composition (product and by-product yields, energy content of solid residue from biochemical processes and indirectly the consumption of energy and chemicals were modified). The reference data was used to develop parametric models of assembly-level capital costs (capacity factored models) and the mass & energy balances (facility level input-output model) were used for variable cost estimation. A common basis was used for fixed operating cost analysis, e.g. wages, overhead costs, or cost of operating supplies were constant or constant fractions of capital cost for all design scenarios. Also, all economic parameters of discounted cash flow analysis were kept the same for each design scenario and thus changed from the assumptions of the reference analyses to one single assumption.

Emphasis was put in the study on the feedstock costs and therefore a comprehensive raw material assessment was conducted. In the analysis public database information of different biobased feedstock availability was used. The transportation costs of the different raw materials delivered to the plant gate were calculated based on biomass availability, transportation distance, transportation method, fuel cost etc.. A maximum availability was set to correspond to the total available feedstock amount in a region of ~150 km around the case pulp mill. Later on in the risk analysis the transportation cost of feedstocks was allowed to vary depending on the fuel cost, and the crop cost or stumpage fee of different biomass options was also varied.

Second main point of interest in the study was the quantification of integration impacts under two pulp mill operating conditions: current operations and pulp mill configuration and modernized mill configuration. Two types of impacts were quantified: 1) structural process integration impacts, using the same utility system and waste handling to the available extent changing the investment costs, and 2) simple overhead cost impact and sharing the existing pulp mill labour force changing the O&M costs of the biofuel production. These impacts were fully allocated to the bioproduct.

A most promising production capacity for each scenario was selected using total production costs of biofuel as criteria: Production costs (including capital charges – 10% capital recovery) were analysed for wide range of production capacities and the lowest cost capacity was selected. No mathematical programming was used, instead a manual comparison was conducted.

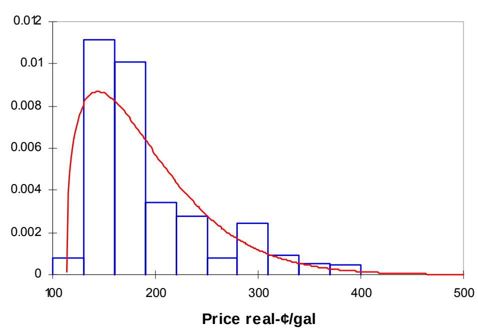
4.3.2 Uncertainty analysis & conclusions

Uncertainty analysis was conducted using two methods consecutively:

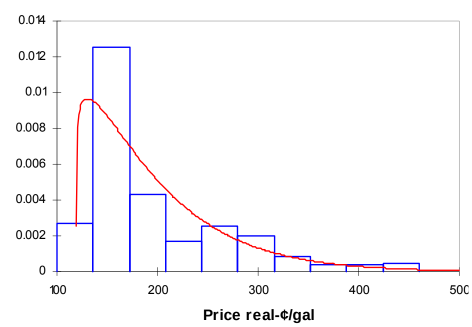
- Sensitivity analysis – evaluation of the impact of external uncertainties on main screening criterion (after-tax IRR)
- Monte-Carlo analysis – evaluation of combined impact of uncertainties having biggest impact on screening criterion based on the sensitivity analysis

Because all main products were considered to be sold as fuels, their prices were assumed to follow energy content corrected gasoline and diesel wholesale prices (less piping costs). Correlation analysis between other raw materials and/or products was not required based on the sensitivity analysis results and data availability: Critical external factors were estimated to be feedstock price of which long term reported historical price data was only available for pulp wood and therefore correlation analysis was not possible for feedstock price; electricity and chemicals were not substantial factors for profitability of the scenarios leading to separate distribution need for main energy source prices. Uncertainties were formulated as probability distributions, definitions for the considered uncertainties are presented in Figure 2.

Prices for ethanol and mixed alcohols were derived from gasoline price and FTL price from diesel price using higher heating value (HHV) of the fuels. Also, the diesel price distribution was used in biomass transportation cost calculation. Coal price was defined as free on board (f.o.b.) price and case specific transportation and fixed costs were added to the base coal price. Oil price trend forecasts from Annual Energy Outlook 2009 by DOE/EIA were used to define exponentially increasing liquid fuel prices and a triangular probability distribution was given, reference scenario was estimated to have the highest probability. Similarly the price trend was defined for lignocellulosic biomass (forest based woody biomass and agricultural waste), here it was assumed that the real price of biomass would not exceed higher quality biomass price (pulpwood) during the forecast period of 20 years and an average price increase would have the highest probability to occur. All other model prices were estimated to increase according to inflation through the analysis period.

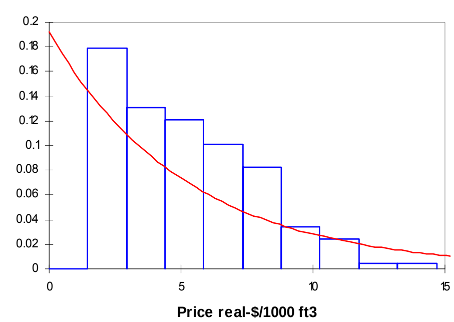


Historical retail gasoline real price (1993-2008) – Weibull distribution

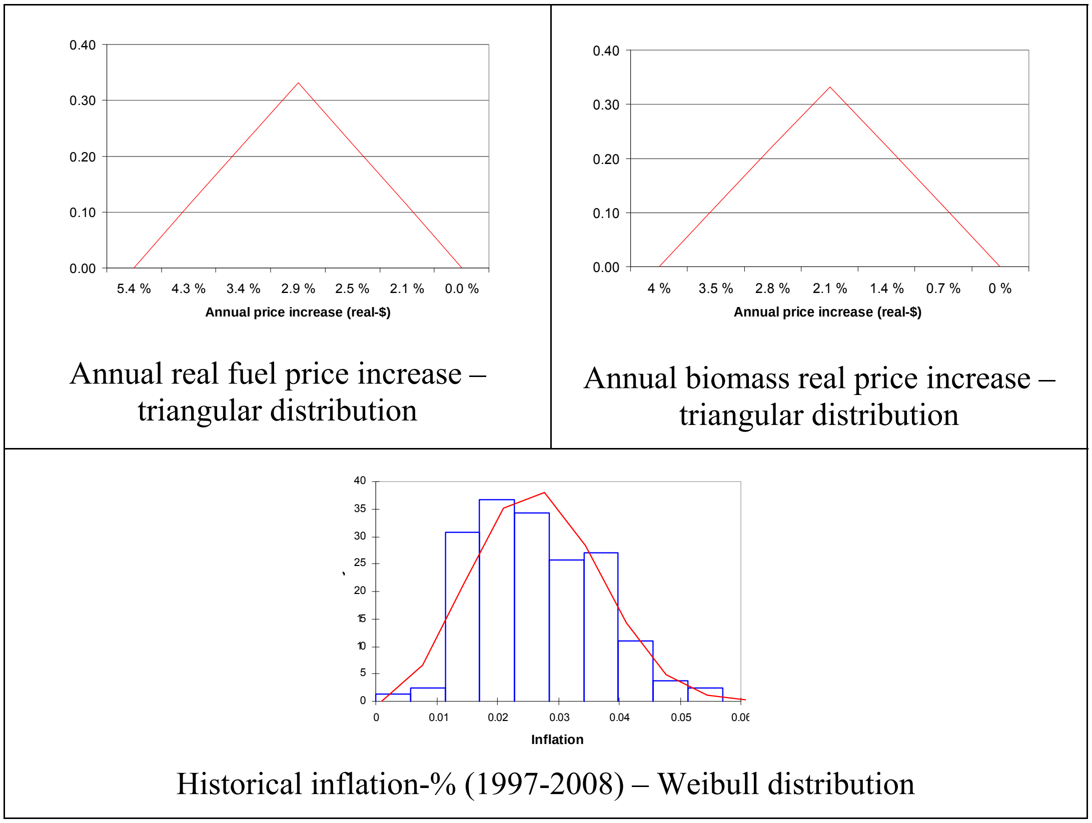


Historical retail diesel real price (1994-2008) – Weibull distribution

Historical lignite coal real price (1949-2007) – Beta distribution



Historical natural gas real price (1997-2008) – Exponential distribution



Annual real fuel price increase – triangular distribution

Annual biomass real price increase – triangular distribution

Historical inflation-% (1997-2008) – Weibull distribution

Figure 2. Monte-Carlo analysis input distributions

Monte-Carlo analysis using 5000 iterations in Microsoft Excel based VBA-code was conducted for all process design scenarios setting the biofuel production capacities to the previously identified most promising production capacities. In Monte-Carlo analysis after-tax IRR was calculated assuming 20 years lifetime after 2 year construction time and 50/75/100 production start-up schedule.

An example of the risk analysis results for biochemical design alternatives is given in Figure 3.

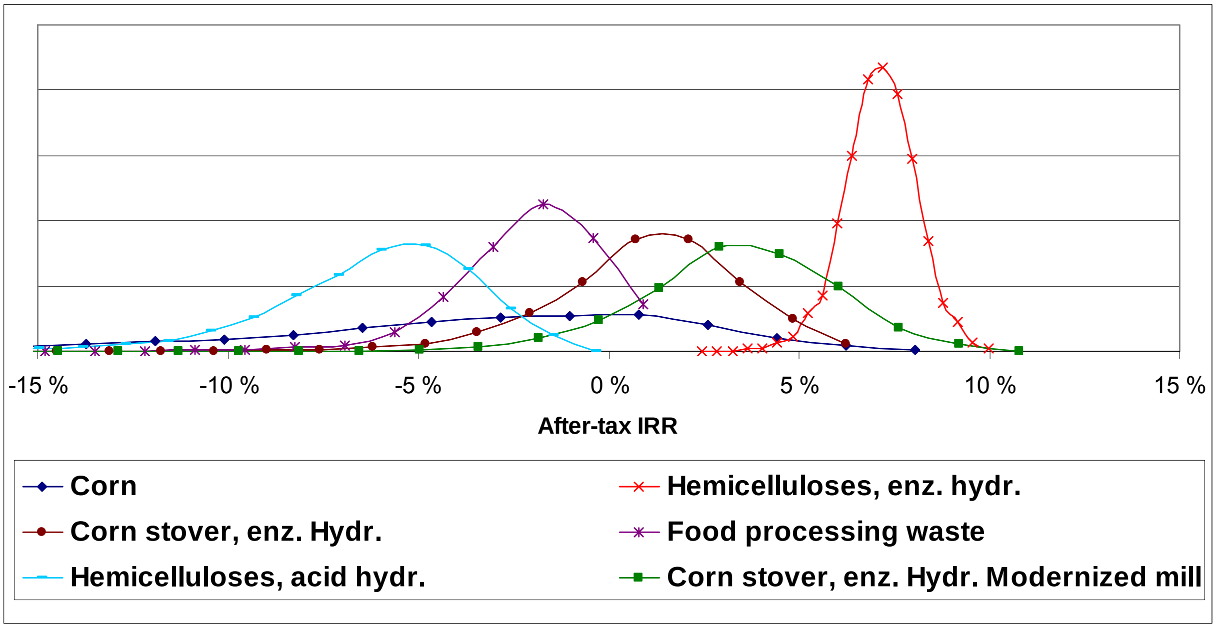


Figure 3. Probability distributions of after-tax IRR of some biochemical design alternatives

From the results is possible to draw several conclusions:

- General conclusions related to the method and its suitability for early stage retrofit design risk analysis
    - Different design options are not only distinguishable based on their expected profitability but also based on the uncertainty of the profitability which enbles screening of alternatives considering the uncertainties
    - It is possible to quantify downside profitability for each alternative, which means the worst case profitability with pre-determined probability. For example using known measure, standard deviation as criteria, 95% confidence interval corresponds to ~2 times standar deviation and the lower bound (-2σ) can be used as systematic definition for downside profitability.
- Screening conclusions
    - Processes having co-products or by-product with revenue potential and not very uncertain prices have substantially lower profitability variation (red line in Figure 3)
    - More costly feedstocks are not promising for the case mill in the case of biofuel production
    - Thermochemical processes seem to have better economic performance in general
    - Among thermochemical design alternatives the simplest option (mixed alcohol production without ethanol separation) seems to be most profitable, however, this product does not have existing markets and needs therefore further consideration before final decision making.
- Integration impact analysis conclusions

- Impacts of integration can be substantial, most important they are for biochemical processes that produce organic solid residue. If no capacity is available for combusting the residues, substantially higher capital investment is required and the profitability is lower (in Figure 3 green line represents a scenario where excess capacity is available whereas the brown line represents a case with no excess capacity)
- Possible benefits of integration are case and capacity (biofuel production capacity) specific

Moreover, as economies-of-scale differ between the design alternatives, substantial differences in promising production capacities and therefore also capital costs were obtained. This raises important questions such as is the assumed financing structure (100% equity financing) possible for all alternatives and how important decision making criterion total capital cost is compared to the profitability measure that was used in screening.

This case study conducted by Hytönen and Stuart considered only external uncertainty sources. This can be partly justified by the assumptions: references were assumed to represent *n*th plant designs, thus process parameter variability (process inherent uncertainties) is relatively low. Nevertheless, the capital investment cost estimates, although relatively having similar accuracy, at the early stage process design are always uncertain. Therefore a capital cost uncertainty (model inherent uncertainty) could have been included in the Monte-Carlo analysis. On the other hand, possibility for capital investment subsidies can in the end offset the uncertainty in capital costs (as it is described in Table 1 the capital cost estimates are often underestimated and thus the final project costs are even 100% higher than the cost estimates at this stage of design analysis). Also, when focusing on one type of uncertainty at a time enables better understanding of the impacts of different uncertainties on the measure that is been used.

The information of uncertainty in profitability was not directly used in screening of design alternatives, however a systematic measure of it was presented and its implications were discussed. On the other hand, it was recognized how important the selection of decision making criteria is and that it is possible to reflect external uncertainties in commonly used decision making criteria such as internal rate of return.

5 Conclusions

Methods for techno-economic analysis under uncertainty at different stages of the design process were reviewed in general and in particular in the context of early stage biorefinery design. Selected biorefinery design analysis case studies were also presented.

Conventional techno-economic analysis is used in early stage biorefinery process design applying the different variants of the analysis methods. For example, capital costs are analysed using methods ranging from simplified plant level capacity factored methods to even detailed equipment data and vendor quotes at the early stage design analysis. Similarly different levels of accuracy are being used for O&M cost estimation. This can potentially lead to additional uncertainty in results because of different levels of precision in the used analysis methods.

Often the goal of the biorefinery design studies is to estimate the capital costs of the developed process and the results are reported with most common profitability measures, NPV and IRR. The simplest risk analysis methods, sensitivity analysis and scenario analysis, are used almost always to identify and better understand the important cost factors of the design(s) in question.

The analysed process designs are commonly assumed to represent *n*th plant implementation of the process and estimates that are based on engineering knowledge of the possible future development of the technologies and sometimes on detailed simulation and modelling of the processes using advanced process simulation platforms. This leads to optimistic process performance which might be possible only in longer term for some technologies. However, the performance of the processes normally evolve to that level relatively quickly after the first implementations and therefore this assumption of well developed processes is justified, especially if longer term aggregated performance measures are used in analysis.

More systematic accounting for all types of uncertainties is not common in early stage design studies. The sensitivity of the main analysis criterion is studied but the variability of the uncertain variables is not always assessed, rather an arbitrary range is selected. Also, often focus is on only one type of uncertainty, giving somewhat biased understanding of the overall risk of investing or continuing R&D of the design. Moreover, the most studied types of uncertainty are process inherent and external uncertainties. Especially external uncertainties are important factors for biorefinery analyses since many of the products are not sold in the current markets and therefore prices and real market demand are unknown. However, in some cases the external uncertainties may not have the biggest impact on the success of the investment and the risk can possibly be mitigated and managed through implementation strategy. Also, some discrete phenomena might be in decisive position for some design alternatives.

Even though some developed optimisation based methodologies have been applied on biorefinery context, they mainly consider uncertainties in the above mentioned manner.

Stochastic risk analysis, especially MC, is often used in process design assessments, normally however more in detailed design phases. It is currently not commonly applied in the context of biorefinery. In some design analyses a systematic correlation analysis is also conducted, for example Ince et al. conclude that correlation analysis did not have substantial benefits: same result (IRR) is achieved with conventional MC approach and when correlations are recognized, the variance is somewhat reduced if correlations are considered [51]. This is however not done systematically in any biorefinery context MC analyses.

Importantly the results of the uncertainty analysis are not always used to their full potential. This can be seen from the use of the results: Whatever the analysed sources of uncertainty are, how they are formulated and their impacts on the screening/selection are assessed, the results of uncertainty analyses are normally only presented and their implications are discussed. Hence, the decision is made using the expected values of the considered decision making criterion/criteria, not based on the quantified uncertainty. Examples of using the actual uncertainty information explicitly in decision making are available and were given, namely the biorefinery studies by Hytonen and Stuart [47] and Cohen et al. [34].

Biorefinery design analyses in the early design stage are not always recognized to be analyses of strategic investments. This important feature of the context should perhaps be given more emphasis in order to be able to better serve the investment decision making: The criteria to screen design alternatives depends on the investment type, for example the project profitability only describes the economic performance of the new operations that are being implemented and they do not reflect company level performance changes. Also the need for using MCDM methods and perhaps even real weighting instead of sophisticated guesses of possible importance of different criteria becomes more important for strategic investment decisions as multiple aspects are changed as a result of the decision, including for example environment and society. This inclusion of several aspects was done for example by Paplexandrou et al. [36] and Cohen et al. [34] who conducted a process creation level process design analysis. However the studies used different basis for the weights, educated guess and expert panel based weights correspondingly.

Integrated biorefinery concepts have been analysed by several authors, mainly in forest biorefinery context. The focus of integration impact analysis has been on structural integration (utilising the existing energy and utility systems) and the impacts are fully allocated to the bioproduct as credits or additional costs. Correctly assessing the impacts and allocating them to all products, for example by using advanced costing methods, can possibly offer substantial benefits to the business decision making on various levels: when correct production costs of all products are known the different product margins can be used as decision making criteria at operational level management of production and also the product and feedstock supply chains.

Nomenclature

AHP – Analytical hierarchy process

CDF – Cumulative Distribution Functions

CO_2 – carbon dioxide

DOE – U.S. Department of Energy

EIA – U.S Energy Information Administration

f.o.b. – Free on board

FT – Fischer-Tropsch

FTL – Fischer-Tropsch liquids

GHG – Green house gas

HHV – Higher heating value

IRR – Internal rate of return

LHS – Latin-hypercube sampling

MC – Monte-Carlo

MCDM – Multi-criteria decision making

MCS – Monte-Carlo sampling

MESP – Minimum ethanol selling price

NPV – Net present value

O&M – Operation and maintenance

PEST – Political/legal, economic, social, technological

PFD – Process flow diagram

PNENW – Present value of ending net worth

PSE – Process systems engineering

PVENW – Present value of ending net worth

P&Id – Piping and instrumentation diagram

ROI – Return on investment

R&D – Research and development

SWOT – Strengths, weaknesses, opportunities and threats

σ – Standard deviation

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APPENDIX G – Conference Paper: Estimation of the cost impacts of retrofit biorefinery implementation using operations-driven costing

Estimation of the cost impacts of retrofit biorefinery implementation using operations-driven costing

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Abstract

Increased competition from low cost pulp and paper producer nations and decreased market demand of pulp and paper products have made it imperative for North American forestry companies to enhance the cost competitiveness of their production facilities. An effort has been made to achieve this by planning to change and diversify the product portfolio with biorefinery products such as biofuels and bio-chemicals either through mill retrofit or repurposing. Risk-adjusted financial justification of many of these strategies is challenging, partly due to uncertainties in the market place for both existing and new products, raw materials in the longer term, and technological viability of potential new biorefining processes in the short term.

We introduce a novel early-stage process design method targeted at estimating the changes in cost-efficiency of existing processes in different retrofit biorefinery implementation scenarios, for screening out non-promising alternatives. The method uses process-based data, process simulation and cost estimation based on the principles of activity-based costing to derive transparent and understandable direct and indirect cost information of an integrated system of continuous processes. Stochastic risk analysis (Monte Carlo) is integrated into the cost modelling framework to be able to analyse the effect of price and performance uncertainties on the cost-efficiency.

Several kraft pulp mill retrofit strategies, including mill modernization and biorefinery implementation projects with different production capacities are evaluated using the proposed method, and the results are presented. Because the method first allocates the costs to activities based on resource consumption and then to end products, the true costs of production can be better estimated. This leads to an understanding of the impacts of process integration on the individual product production costs in the integrated system. Differences – and the reasons for these differences – in cost-reduction potential and overall margin improvement, and therefore also in project profitability and mill's economic performance can be seen and analysed between retrofit strategies. The difference in the level of uncertainty, analysed in a systematic manner, shows that screening out retrofit strategies requires the use of multiple decision making criteria.

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Introduction

A forest biorefinery (FBR) through retrofit modification of existing pulp and paper mills has been in focus of many recent biorefinery design studies. For example, Mao et al. and Amidon et al. have reported latest developments in near-neutral and hot water extraction of hemicellulose prior to pulping (VPP) –processes [1, 2], and Larson et al. have published a comprehensive study considering thermochemical black liquor conversion into biofuels and pulping chemicals [3]. This FBR approach is aiming at concurrently maintaining the core business profitable and generating new revenues by integrating bioproduct production into the P&P mill. The benefit compared to greenfield FBR plants is considered to come from lower capital cost requirement because existing pulp mill systems can be utilized instead of investing into all utility and service activities. Also the credit from possibly decreased core business production costs is expected to make the biorefinery perform better financially. Another approach for forest biorefinery has also been presented: Phillips et al. have analysed the economic potential of repurposing a shut-down kraft pulp mill into a biochemical bioethanol plant [4]. This presents the same capital cost benefits, even higher capital cost reductions can be realized since all old pulp mill equipment is available.

Retrofit biorefinery implementation will compete with traditional capital projects such as pulp & paper mill production rate ramp up or replacement of old boilers. The potential of advanced costing methods such as activity-based costing (ABC) –like operations-driven costing has been demonstrated in retrofit design decision making context by Janssen et al. and Laflamme-Mayer et al. [5, 6]. They used this method for analysis of traditional retrofit projects for newsprint mills in order to have better cost information for design decision making and supply chain (SC) optimisation. In both cases one product was produced at time (paper), hence the full potential of ABC in multi-product -costing was not needed. This is naturally the case of a retrofitted forest biorefinery which produces several products concurrently.

The current state of biorefinery technology development is still in some cases far from commercial implementation. This gives rise to additional uncertainties besides the external uncertainties of market place – even though ethanol and other biofuels have high demand their prices have shown detrimental volatility in the past; also the nature of emerging biorefinery industry might substantially increase the cost of biomass. These uncertainties have commonly been considered in biorefinery process design mainly using sensitivity and scenario analysis, some authors also report the use of stochastic method (Monte Carlo analysis) in design analysis [7, 8].

Objectives

Overall objective of this study is to demonstrate the use of operations-driven costing and stochastic risk analysis in retrofit biorefinery implementation analysis using a real Kraft pulp mill as a case study. More specifically the goals are 1) to illustrate how better understanding of integration impacts on core business manufacturing costs can be obtained in order to clearly see which product (pulp and/or bioproduct) is responsible of generating the profits, and 2) to show how the obtained credit from lower core business manufacturing costs impacts the overall profitability of the retrofit projects.

Methodology

A four-step methodology was applied to the case study:

1. Development of the base case kraft pulp mill:
    - Definition of analysis boundaries
    - Development of a steady-state simulation model of existing processes
    - Validation of the process model
    - Development of operations-driven cost model of the base case operations
    - Validation of the cost model using mill financial data
    - Definition of productivity/efficiency and cost/price development over the analysis period
2. Development of retrofit design scenarios:
    - Definition of retrofit projects (feedstock, product, production scale)
    - Modification of the simulation model (addition of new process equipment/departments, integration of processes)
    - Addition of cost model structural units for new process departments in the mill cost model
    - Definition of efficiency, cost/price development over the analysis period related to new processes
3. Economic analysis:
    - Process simulation → Process parameter values (resource and activity drivers of operations-driven cost model)
    - Cost model simulation → Economic performance of the retrofit alternatives
    - NPV & IRR of the investment project
    - Core business impact measured with pulp production cost reduction
4. Risk analysis:
    - Risky cost model parameter identification
    - Definition of probability distributions of risky parameters
    - Monte-Carlo analysis → probability distribution of economic indicators
    - Downside project profitability (expected value - 2σ → 97.5% certainty that profitability is better than this value)

Case study

Base case P&P mill and analysis boundaries

The case study base case is a North American hardwood Kraft pulp mill producing slush and wetlap pulp (~50% dryness) for fine paper production. The paper mill (integrated into the pulp mill) is not considered in this case study, since the actual intermediate product pulp is assumed to be saleable with adjusted market pulp price for the economic analysis purpose.

Since the mill in question has also options for modernization as a pulp and paper producer, a second “Modernization Case” is set forth as another basis for evaluating different biorefinery options.

More detailed mill description and raw material costs delivered to the case mill are reported by Hytönen and Stuart [8, 9]. Based on their conceptual design level process analysis, three design alternatives were selected for the pre-feasibility level design analysis using more detailed analysis procedures. These biorefinery alternatives are described in the next part.

The analysis considers pulp mill process and all retrofit design alternatives without waste water treatment plant which is not located at the pulp mill site. In addition to waste water treatment, cooling water and oxygen are considered as fixed price utility to the analysed processes, consumption is based on simulation model. Electricity consumption is estimated based on mill’s historical power consumption at process department level and estimated changes due to process changes in retrofit, biorefinery process electricity demand is calculated from reference estimates. Capital cost estimates are outside battery limit (OSBL) cost estimates, thus infrastructure required for operation is also accounted for.

Retrofit design alternatives

Table 1 lists the retrofit design alternatives considered in this study. One of these design scenarios is the “Modernization Case” alone (first alternative). All biorefinery alternatives have two design scenarios: integration into base case mill or modernized mill case. This results in total of 11 retrofit design scenarios.

Table 1. Retrofit process alternatives and their specifications (based on [8, 9])

Feedstock	Process description	Products	Design capacity	Feedstock capacity
Pulpwood	Modern Kraft pulping process and chemical recovery cycle utilizing maximum amount of existing pulping process equipment	***Kraft pulp***	1650 BDT pulp/day (35% increase from base case capacity)	1.5 million BDT/year
Hemicellulose extract	Value-prior to pulping (VPP): Near-neutral green-liquor extraction Acid hydrolysis Liquid-liquid separation Fermentation & distillation	***Ethanol*** Acetic acid Furfural	base case - 6.1 MMGPY	10% of pulp wood
			modernized - 8.0 MMGPY	10% of pulp wood
Corn stover Co-processed with kraft pulp, using mill infrastructure to maximum extent	Biochemical lignocellulosic ethanol: Dilute acid pre-treatment Enzymatic hydrolysis Fermentation & distillation	***Ethanol*** Organic solid residue	25 MMGPY	0.25 million BDT/year
			100 MMGPY	1 million BDT/year
Forest residues Bark co-processed with kraft pulp, using mill infrastructure to maximum extent	Thermochemical Fischer-Tropsch: Drying & grinding Steam reforming Syngas cleaning and compression FT-synthesis	***FT-liquids*** Energy	37 500bdt/year	0.25 million BDT/year
			150 000 bdt/year	1 million BDT/year

Further key process design assumptions are given in Table 2, the listed references are used as the basis for process designs and the capital cost estimates. Mass and energy balances of the processes are developed using steady-state process simulator.

Table 2. Process assumptions

Retrofit option	Key process assumptions	References
VPP	10% extraction rate (of pulp wood) Extraction enabled with and additional extraction vessel Anthraquinone added to preserve same overall pulp yield and pulp properties (dose 0.05% of chips) Pulp production rate (in base case and modernized mill case) maintained	[1, 10, 11]
Corn stover-to-bioethanol (25 MMGPY)	In base case pulp mill configuration solid residue replace coal and added steam demand met by natural gas boiler steam Power boilers solids load constrained Natural gas boiler has excess capacity Boiler investment avoided In modernized mill configuration solids burned in power boilers that have excess capacity	[12]
Corn stover-to-bioethanol (100 MMGPY)	In base case pulp mill configuration new boiler and turbine capacity installed In modernized mill configuration solids burned in power boilers that have excess capacity	[12]
FTL-process (37 500bdt/year)	Single-pass FT synthesis, tail gas burned in lime kiln to replace natural gas and excess burned in natural gas boiler Existing turbines used Steam surplus adjusted by lowering coal use in power boilers	[3, 13, 14]
FTL-process (150 000 bdt/year)	Single-pass FT synthesis, tail gas burned in lime kiln to replace natural gas and excess burned in natural gas boiler Additional turbine installed in base case (modernized mill scenario has excess turbine capacity installed) to utilise generated high pressure steam and excess steam generated from tail gas Coal use decreased to lower steam generation	[3, 13, 14]

In Table 3 the total project investment costs of considered retrofit alternatives are presented. Values are total installed capital costs of required new process equipment and the potential capital cost reduction based on the mill's existing infrastructure and equipment constraints described in Table 2 are considered. The reference capital costs are escalated to 2010-$ using Chemical Engineering Plant Cost Index (CEPCI) and scaled-up using the method and factors described by Hytonen and Stuart [8]. Values are assumed to be n*th* plant cost estimates.

Table 3. Total project investment cost of retrofit alternatives

Retrofit alternative	Capital cost (M$)	Remarks
Mill modernization	285	New evaporator plant, recovery boiler, lime kiln and additional steam turbine Power boilers, causticizing and fiberline retrofitted
Base case – VPP	47	Additional extraction vessels (2) in front of continuous Kraft digesters Sugar stream conditioning (liquid-liquid extraction, liming)
Base case – corn stover-to-ethanol (25 MMGPY)	58	No additional boiler
Base case – corn stover-to-ethanol (100 MMGPY)	233	Includes additional boiler and turbo-generator
Base case – FTL (37 000 bdt/year)	117	
Base case – FTL (150 000 bdt/year)	332	
Modernized mill – VPP	57	
Modernized mill – corn stover-to-ethanol (25 MMGPY)	58	No additional boiler
Modernized mill – corn stover-to-ethanol (100 MMGPY)	151	No additional boiler and turbine required
Modernized mill – FTL (37 000 bdt/year)	117	
Modernized mill – FTL (150 000 bdt/year)	302	

Accuracy of the capital cost estimate is assumed to be -10%…+15% and -15%...+25% for the mill modernization and biorefinery projects correspondingly. This reflects the higher uncertainty in new biorefinery process technologies compared to traditional pulp mill processes/process parts. Even though the level of detail in the reference studies for capital cost estimates was not the same, the assumed ranges were selected to represent all design scenarios. Investment schedule for mill modernization is assumed to be three years (20/30/50) and for biorefinery projects two years (30/70), both starting at 2010, thus simultaneous retrofit is considered in modernized mill cases.

Assumptions used in operations-driven costing

Table 4 describes the cost allocation rules including variable, fixed and investment cost categories. Variable costs are traced by the cost model based on resource and activity drivers defined in the table. Fixed costs and investment costs are allocated and assigned using the given basis through dedicated cost drivers correspondingly.

Table 4. Cost allocation bases used in operations-driven cost model

Category	Cost type	Allocation basis
Fixed	Labour	Current mill employees shared, labour costs allocated based on headcount • Feedstock preparation (yard & mobile equipment) shared up to the level that is sufficient for pulp process requirement • Maintenance crew and supervisors shared • Other shift operators, laboratory technicians and supervisors shared New employees hired if design requires and all allocated to biorefinery
	Maintenance	Annual budget set for pulp mill and biorefinery departments separately Maintenance supplies for biorefinery – 2% of initial capital investment
	SG&A, benefits	Headcount
	Other fixed (operating supplies, outside services)	Annual budget set for pulp mill and biorefinery departments separately
Variable	Water	Clean water consumption
	Energy	Fuel cost shared based on steam demand Fuel production (solid residues, tail gas) credited
Investment	Investment	Energy system (additional boiler and utility system) capital investment cost shared based on steam consumption Mill modernization capital costs in commonly used departments allocated fully to pulp mill

The allocation rules listed in Table 4 are not the only possible rules, for example energy costs could be allocated based on source of the energy: pulp mill produces as by-products black liquor and bark which are used in steam and electricity generation. These low resource cost activities could also be directly traced to the pulp. Moreover, the excess steam and electricity can be “sold over-the-fence” to external processes such as paper mill and biorefinery with a fixed price. If the integrated facility requires more steam and/or electricity than can be generated from the black liquor and bark, the costs of fossil fuels and purchased electricity should be allocated based on the energy demand. Compared to above allocation rule, this would increase the cost of steam for biorefinery and paper mill and at the same time lower energy costs of pulping process.

In Table 5 all parameters that are expected to have different future trend than consumer price index (CPI) or producer price index (PPI) are listed. Also the uncertainty in the trends is given for most important parameters. The biorefinery product prices are assumed to follow oil price trend (all products are fuels).

Table 5. Future trends of input parameters

Parameter	Annual Inflation (%)	Trend standard deviation (Normal distribution)	Remarks [reference/data source]
Prices & costs			Price/cost trends in real-$
• Pulp	-0.5	0.5	[15]
• Oil	2.0	1.0	[16]
• Pulp wood	1.5	0.75	
• Forest residues & agro residues	2.5	1.25	
	0.25	-	
• Labour cost	0.5	-	
Annual capital expenditures	CEPCI	-	25% to development (cost reduction) and 75% to replacement (regulatory, quality and reliability)
Productivity & efficiency			Annual development capital expenditures with 2 years payback time and division 50% fibre, 40% chemicals and 10% energy cost reduction result in different productivity gain in every scenario
• Fibre productivity			
• Energy efficiency			
• Chemical productivity			
• Labour productivity	0.5	-	Annual replacement capital expenditures achieve additionally labour productivity and production reliability increases
• Pulp production reliability	0.25	-	

In addition to long term trend uncertainty, many prices have short term uncertainty (volatility). In this retrofit design assessment following price volatility is considered:

- Raw materials – normal price distribution, 5% standard deviation from expected price at the mill gate is assumed
- Gasoline (ethanol) – Weibull distribution (β = 1.336, γ = 0.846 and μ = 1.14 in \$/gal) [17]
- Diesel (FT-liquids) – Weibull distribution (β = 1.125, γ = 0.819 and μ = 1.19 in \$/gal) [17]
- Pulp – normal price distribution, 10% standard deviation from expected price [15]
- Natural gas – truncated exponential price distribution (λ = 0.192, min = 2.1 and max = 13.7 in \$/MMBTU) [18]
- Electricity – Weibull distribution (β = 1.55, γ = 0.752 and μ = 5.46 in ¢/kWh) [19]

Results and discussion

Manufacturing costs

In Figure 1 and Figure 3 the production costs of pulp and biofuels in all design scenarios, using the above described cost allocation rules and analysis method, are presented. Costs are divided to variable and fixed production costs of mill areas or process departments, where pulp mill area costs are aggregated costs of several departments for clarity reasons (e.g. fiberline consists of total 8 departments).

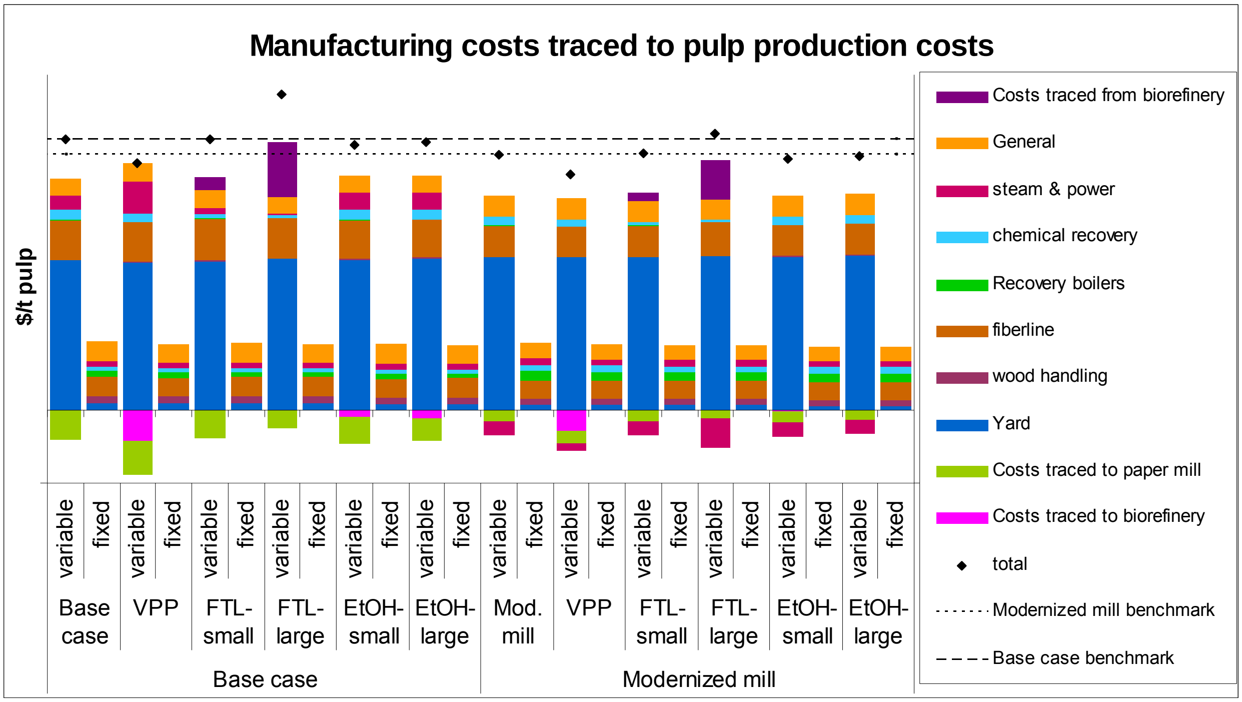

Figure 1. Variable and fixed pulp production costs in pulp mill areas and the total costs traced to pulp in considered design scenarios

Total costs of pulp mill areas that are traced to pulp manufacturing costs vary significantly between design alternatives. Highest pulp production costs are seen in both pulp mill configurations with high production rate FTL process followed by small capacity FTL process alternatives. Lowest costs are observed in both VPP retrofit scenarios; corn stover-to-ethanol alternatives present comparable pulp production costs with their corresponding base case.

The total fixed cost of pulp mill activities (including labour, maintenance, business unit and corporate overheads and depreciation) do not change substantially between retrofit scenarios. This is the result of combined effects of increased depreciation costs and decreased other costs: New asset implementation increases depreciation costs whereas when absolute amounts of business overhead and labour costs are not assumed to change, their cost per ton is decreased. In addition, the fixed cost allocation to new biorefinery processes seems to lower only slightly the overall fixed costs that are traced to pulp manufacturing costs. The decrease from base case is the largest in high biofuel production volume cases, about 10$/bdt of pulp.

In variable pulp production costs substantial variation is observed. The main changes occur in steam & power, recovery boilers and chemical recovery areas. In Figure 2 more detailed cost breakdown of steam & power area is shown including variable and fixed costs and also the traced costs between this area and pulp mill and biorefinery. It reveals the impacts of different available bio-based fuels on fossil fuel requirement for meeting the process steam demand – the costs of fossil fuels and credits from net electricity production change substantially between design scenarios (pulp mill and biorefinery electricity demand is already reduced from total electricity generation and not shown in Figure 2). The net steam & power area costs traced to end product pulp vary from base case -14$/bdt pulp to highest value of 74 $/bdt pulp in small FTL design scenario implemented into base case mill and to lowest value of -34 $/bdt pulp in modernized mill scenario. Highest costs can be explained by lower available black liquor amount due to hemicellulose extraction and increased process steam demand, which in turn increases the demand for natural gas based steam (coal also used to its maximum extent). The lowest area costs in all modernized mill scenarios on the other hand are result of higher energy efficiency in pulping process (no natural gas is needed and excess electricity is generated) and excess of bio-based fuel (either tail-gas from thermochemical process or organic solids from bioethanol process). Also coal demand varies depending on the scenario.

Similarly other process areas with substantial cost variations between scenarios can be analysed. The impact of selected allocation rules can be examined by drilling down to traced costs.

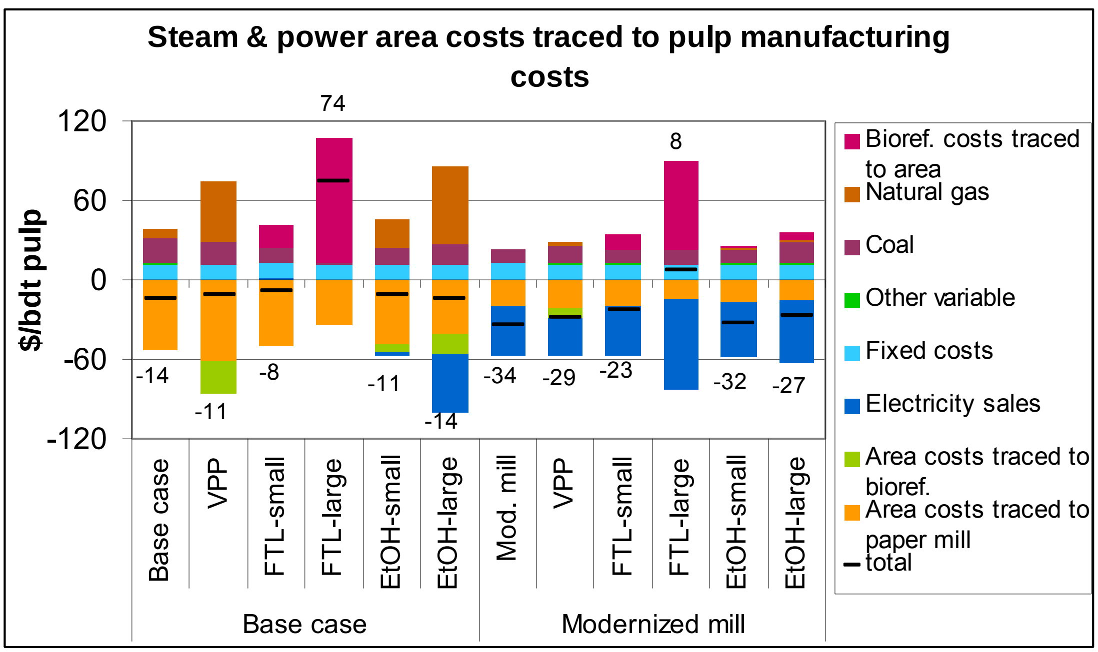

Figure 2. Variable costs of steam & power area at the pulp mill

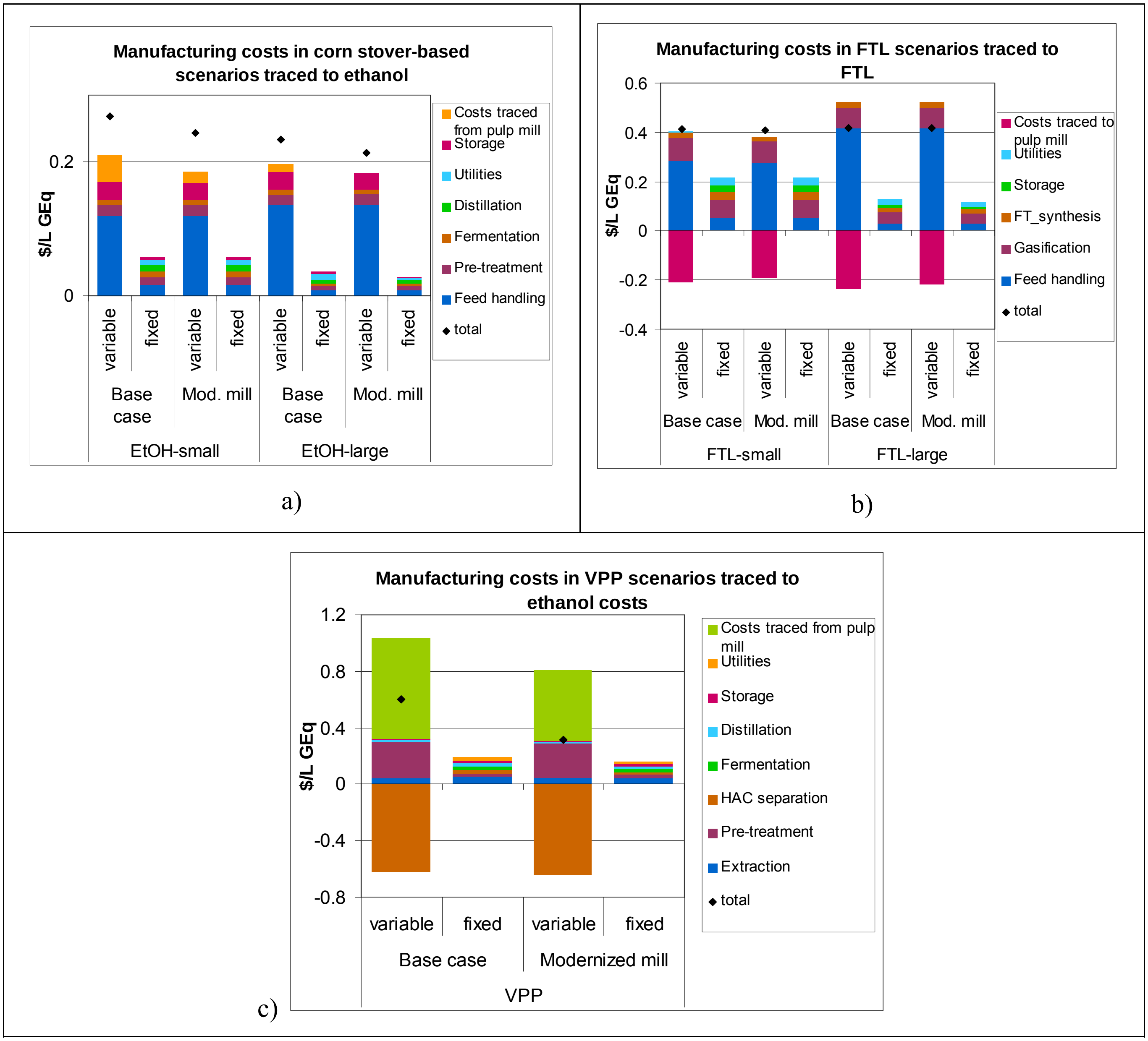

Figure 3. Biofuel production costs in gasoline equivalent litres. a) corn stover ethanol design scenarios, b) FTL design alternatives and c) VPP design alternatives

Biofuel production costs vary between 0.22 and 0.6 $/GEg litre, the corn stover based ethanol processes having lowest production costs and VPP alternative implemented in base case mill the highest production costs. Important to notice is the magnitude of the costs traced from/to pulp mill: the VPP processes have substantially lower production capacity but relatively high energy demand (selected allocation basis: all steam needed in extraction is traced to biorefinery process department) and cost transfer is therefore higher from steam & power area. Contrary to that, FTL process designs generate substantial amount of tail-gas that is a key credit for the biorefinery process. In VPP design scenarios additional credit is obtained from sold acetic acid and furfural.

Profitability and risk analysis

The profitability of a retrofit project is defined here to include all credits from changed pulp profits compared to the corresponding base case. In modernized mill scenarios the changes in profit from current mill operations due to mill modernization are not included, hence, the profitability is evaluated for biorefinery projects alone (mill modernization also assessed separately as a retrofit alternative). Two measures for profitability were applied, net present value (NPV) using 11% rate of return, and internal rate of return (IRR).

Results of Monte Carlo (MC) analysis are used for obtaining both project profitability and risk level, expected and downside profitability respectively. The downside profitability represents the value above which the profitability is expected to be with ~95% certainty, mathematically defined as expected profitability minus two times standard deviation. In MC analysis 200 iterations was conducted (Monte Carlo analysis using operations-driven cost model is computationally heavy), more iterations were tested and no significant change in either target measure, expected or downside profitability, was observed. The results are shown in Figure 4.

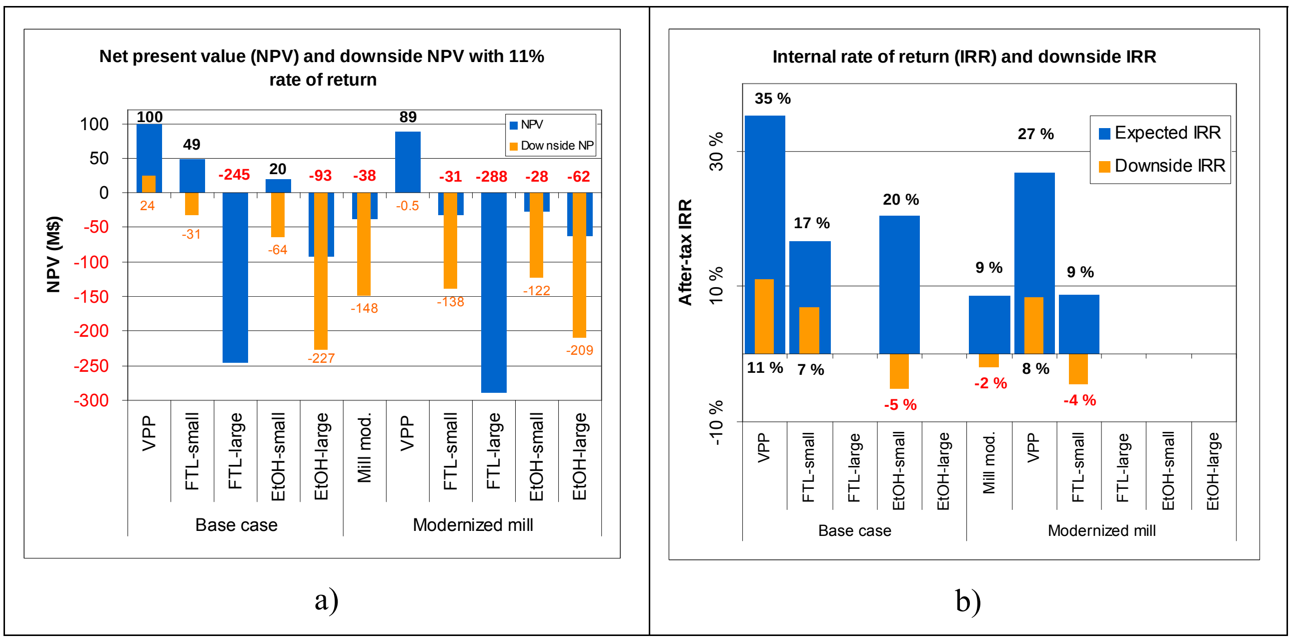

Figure 4. Profitability of analysed retrofit projects. a) Net present value and downside NPV, and b) internal rate of return and downside IRR

From the results it can be seen that many of the retrofit project show low and even highly negative profitability if it is measured with fixed rate of return of 11% and NPV. However, many of the projects have positive expected IRR. The expected IRR and downside IRR are presented only for projects that have positive expected IRR, thus for all projects having positive NPV with 0% rate of return. Using this break-even performance as screening heuristic (instead of e.g. 11% weighted average cost of capital (WACC) which is commonly considered to be minimum rate of return for strategic investment projects) makes sure that we do not screen out a possibly promising retrofit alternative but also is able to remove projects that most probably will not be profitable. Moreover, this heuristic lowers the probability to obtain such annual discounted cash flow series that change sign several times over the project lifetime. Therefore it enhances the reliability of the IRR estimate. However, in small ethanol retrofit project and mill modernization project scenarios ~25% of the iterations generated such cash flow series that do not have IRR solution and therefore these samples were not considered in the probability distributions shown in Figure 4 b).

The VPP projects appear to have highest expected IRR in both mill configurations, however it must be noted that in modernized mill case the value does not include the mill modernization project's impacts. This profitability value differs notably from reported value by Mao et al. [1]: differences between assumptions (costs traced outside the analysis boundaries, annual productivity/efficiency improvements and inflation for different resources) lead to substantial pulp production cost reduction and higher profit in this study compared to no annual cost reduction in the study by Mao et al. In addition, the changes in all common activity costs have influence beyond the analysis boundaries, namely on the papermaking costs. These impacts are not explicitly considered in the profitability measures of this study.

Downside NPV is positive only for the VPP alternative, downside IRR values show that the mill modernization project alone as retrofit project has lowest risk (standard deviation smallest) but it has slightly negative downside IRR value. VPP alternatives have because of their high expected profitability the highest absolute value of the downside IRR. All analysed biorefinery projects have relatively similar risk, and the small FTL project has the only other positive downside IRR in addition to VPP projects.

Compared with a design alternative pre-screening analysis using the same retrofit alternatives and case mill conducted by Hytönen and Stuart (conceptual level design analysis considering integration into base case mill with no impacts on pulp production costs estimated and fixed prices for common utilities and services [8]), all expected IRR values obtained with the presented method are somewhat improved. On the other hand their risk level seems to be relatively much higher, this can result from the additional uncertainties considered in this study compared to the pre-screening – project investment cost uncertainty and pulp price variation – and the fact that also the changes in pulp production costs are credits/additional costs to the retrofit projects.

Conclusions

A pre-feasibility level techno-economic assessment of different biofuel production scenarios at a North American hardwood pulp and paper mill was conducted using operations-driven costing combined to Monte Carlo risk analysis. Activity based costing –like cost accounting method was based on validated steady-state simulation model of the case study pulp mill and models of considered biorefinery process alternatives integrated into the pulp mill model.

Using the presented set of allocation and tracing rules, substantial manufacturing cost differences between retrofit design alternatives are observed for both pulp and the biofuels. These differences can be further analysed by drilling-down to individual resource consumption and fixed costs assigned to each process department because of the structure of the costing method that was used. If other allocation bases would be utilised, these differences would naturally be different, however the important fact to notice is that the core business production costs are changed and differences in this change between different biorefinery processes exist. The impacts of allocation rules on the final results should also be assessed before selecting the appropriate allocation basis.

The combined effect of manufacturing costs of the two concurrent products and their respective sales prices on project profitability showed also significant differences between analysed retrofit projects. Clearly the most promising project among the analysed cases is the near-neutral VPP alternative. Another key conclusion is that small capacity processes seem to have better profitability compared to same processes with higher capacity. This can be partly explained by the relatively higher capital cost due to required additional boiler and turbine capacity.

The presented measures for biorefinery retrofit implementation project performance analysis, changes in core business manufacturing costs and project profitability and downside profitability, all show similar behaviour: Highest expected IRR project (VPP) is clearly the best retrofit project if NPV is used as a measure, however the relative risk in that project is high compared to the traditional retrofit project (mill modernization). In addition, based on the operations-driven cost analysis, this project relies on high revenues from by-products (acetic acid and furfural). Hence, it can be concluded that it is imperative to analyse retrofit biorefinery projects using a set of criteria instead of only one singe indicator of performance to enable better informed decisions in capital appropriation process. Especially the analysis of the changes in the performance of core operations seems to have an important effect on the profitability of the retrofit projects. However, it is important to notice that in this specific case of integrated pulp and paper mill, the integration impacts reach also beyond the pulp mill and that these impacts, especially the changes in energy costs, should not be neglected in the decision making. This issue should be studied in future.

In addition, in the case of stochastic risk analysis the suitability of the metric must be carefully addressed: calculation of IRR from sign changing cash flow series that are possibly obtained as a results of Monte Carlo sampling for relatively low profitability design projects, poses a risk of having several solutions. Other measures can be used in these cases, for example NPV or modified internal rate of return (MIRR).

Acknowledgements

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APPENDIX H – Conference Paper: Techno-Economic Assessment and Risk Analysis of Biorefinery Processes

21st European Symposium on Computer Aided Process Engineering – ESCAPE 21
E.N. Pistikopoulos, M.C. Georgiadis and A.C. Kokossis (Editors)

Techno-Economic Assessment and Risk Analysis of Biorefinery Processes

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Abstract
Biorefinery process design generally follows the principles of traditional chemical process design, however some unique characteristics of the forest biorefinery (FBR), especially the large number of distinct strategies and current process development stage, causes significant uncertainty in process design decision making.
This paper examines the challenges in the analysis of FBR techno-economic performance under uncertain conditions. It briefly reviews different methods used in process design uncertainty analysis, and the strengths and weaknesses of commonly used risk analysis methods. Moreover, the use of risk analysis in selected recent forest biorefinery design studies is reviewed.
A case study is presented in which Monte Carlo analysis is used in screening different biofuel retrofit FBR design alternatives.

Keywords: Biorefinery, process design, techno-economic analysis, risk analysis

1. Introduction

1.1. Techno-economic design analysis under uncertainty
In process design sources of uncertainty can be classified as a) model-inherent, b) process-inherent, c) external and d) discrete based on their nature [1]. Especially the external uncertainties (e.g. uncertainties at company, industry or general environment levels [2]) are of interest at the early design stages which focus on screening and selection at a higher, strategic level of design decision making. All different uncertainties can be identified, quantified and formulated for risk analysis using qualitative or quantitative methods.

1.1.1. Qualitative risk analysis in design
Qualitative risk analysis is considered a prerequisite for traditional process design activities such as process creation or concept demonstration and more detailed quantitative risk analysis. For example, SWOT (Strengths, Weaknesses, Opportunities, and Threats evaluation) or PEST (Political, Economic, Social, and Technological analysis), commonly used in strategic planning and in capital spending planning, use

verbal and subjective "quantification" of governing internal and external factors (and their uncertainties) under generic and qualitative conditions to get a benefit-disadvantage description of each considered strategy.

1.1.2. Quantitative risk analysis in design

Deterministic or stochastic methods can be used to formulate uncertainties:

- Deterministic methods – input uncertainties (all values inside ranges have equal probability) are propagated into output uncertainty using the techno-economic model. Example methods are sensitivity analysis, scenario planning and different scoring and discounting methods.
- Stochastic methods – uncertain variables are quantified using their probability distribution and propagated into output uncertainties. Calculation time of computationally heavy analyses (such as Monte-Carlo analysis) can be minimized using advanced sampling methods such as Latin Hypercube sampling (stratified sampling) or random walk sampling (Markov chain Monte Carlo). Also, propagation of variance methods can be used for estimating expected values and variances.

Optimization under uncertainty is a group of problem formulation methods applicable to quantitative risk analysis. Depending on the goal of the design analysis and the information availability, the most suitable formulation of uncertainties and the optimization method are selected: e.g. for finite number bounds or fixed parameter values to describe the uncertainties, deterministic optimization under uncertainty can be used. If these model parameter combinations (scenarios) are given a probability, the occurrence of the scenarios is then also the probability of the corresponding result. Another example is stochastic programming which uses probability distributions or the knowledge of the analysts (called deterministic stochastic programming) to arrive at the uncertain model parameters. For example Sahinidis has reviewed different methods to solve stochastic programming risk analysis problems [3].

A common challenge to all quantitative methods is objective quantification of the prevailing uncertainties: when using scoring methods which rely on ordinal verbal scales, perception and setting of the severity of each risk factor, and the perception of the scales in use, can differ between people leading to subjective risk analysis [4]. Similarly in the use of stochastic methods, probability distributions are perceptions of real distributions and can therefore reflect a lack of analyst knowledge [5].

A critical and generic task in risk analysis is the recognition of the sources and types of uncertainties. The overall techno-economic analysis goals and design decision-making objective should be considered together to define the most suitable analysis method.

1.2. Techno-economics and uncertainty sources in the forest biorefinery context

Techno-economics of lignocellulosic-based biorefineries in general will be similar to those of the petroleum-based industry and corn-based biorefining [6, 7] including characteristics associated with the design of processes with low margins, multi-feedstocks, diversified product portfolios and high capital intensity. The lignocellulosic biorefinery design and techno-economics however should consider certain key issues:

- Process-inherent uncertainties (e.g. product yields) for new emerging biorefinery process technologies can be significant, compared to mature process technologies.

- Feedstock and product markets are evolving continuously compared to more stable petroleum industry. Thus, external market factors are partly unknown and uncertain.
- Models describing phenomena at the unit operations level, and at the business level, need to be simple because of unknown scaling and transformation of laboratory/pilot scale process knowledge and the business environment knowledge to the biorefinery process and business models.
- Discrete uncertainties such as policies (investment subsidies or product incentives, and environmental policies) or availability of financing are especially uncertain in the biorefining context

From the many types of uncertainty, to date mostly external uncertainties have gained attention in published early stage biorefinery design studies. Also, mainly the simplest deterministic and stochastic risk analysis methods have been employed (scoring or sensitivity or scenario analysis, and Monte-Carlo analysis respectively) [8].

1.2.1. Risk analysis in recent biorefinery design studies

Cohen et al. used scoring method to formulate process inherent uncertainty of selected emerging technologies for ethanol production in an integrated forest biorefinery [9]. The technical maturity level of different processing steps of ethanol production processes was given a qualitative maturity score. The importance of this uncertainty was assessed using a panel based multi-criteria decision making process (other decision making criteria included profitability, environmental and energy related criteria). The risk criterion was weighted the third most important among the criteria in the study context.

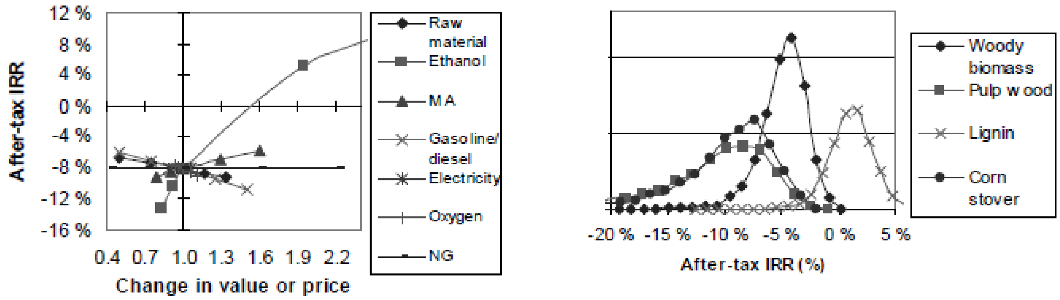
At higher level of detail, Kazi et al. [10], Laser et al. [11] and Larson et al. [12] have used scenarios and sensitivity analysis for evaluating the impacts of external uncertainties (end-product and energy prices) on financial performance of design alternatives. Process designs all focused on biofuel and bio-energy production in greenfield or integrated setting (integration into kraft pulp mill). Risk analysis was not explicitly in the focus of the design analysis, but rather it was conducted to better understand possible impacts of variations in business environment. It was also not explicitly used in the design decision making even though substantial effort was made to quantify risks.

2. Biorefinery Case example

An early stage design techno-economic analysis of a pulp mill FBR was presented by the authors [13, 14]. Various biofuel retrofit design alternatives were constructed.

Key focus items in the large-block design analysis were 1) raw material cost analysis for all available feedstocks in the mill region and 2) process integration impact analysis. The biorefinery processes were utility-integrated into pulp mill, and mill fixed costs (labor and overheads) were shared to the maximum extent in each design scenario. This integration potentially leads to significant capital and O&M cost benefits compared to corresponding greenfield installations, as was discussed in [13].

Two methods were used consecutively to arrive at risk quantification: sensitivity analysis was used to examine the impact on project profitability due to variations in external factors, and to identify *risky* variables (having substantial impact on performance criteria and significant variation), see example in Fig. 1 a). Independent uncertain variables considered were fossil fuel, electricity and feedstock prices, inflation, and future fuel and feedstock price trends. Biofuel product prices were assumed to strongly correlate with fossil-based fuel prices (price conversion using higher heating values). Monte-Carlo analysis with 5000 iterations was conducted using Microsoft Excel based VBA-code (simulation of one design alternative required 45 seconds), see example in Fig. 1 b).



a) b)

Figure 1. Examples of risk analysis for design alternatives using gasification, mixed alcohol synthesis and ethanol separation: a) sensitivity analysis of corn stover –based alternative, b) after-tax IRR probability distributions of four different feedstock –based alternatives [14]

Downside profitability was used as risk measure, defined as the expected profitability less 1.96 times the standard deviation of it. This gives the 5^{th} percentile value, or the value above which the project profitability is with 95% certainty. For example, from brown line in Fig 1. b) the downside profitability can be observed to be -17%, which can not be obtained using the sensitivity analysis of the same design (Fig 1. a)).
This systematically-quantified downside profitability was used with expected project profitability to screen-out less promising retrofit FBR alternatives for the case mill.
Clear differences in variances and expected profitability between retrofit FBR alternatives were observed and lower risk level or profitability designs could thus be identified. However, the trade-of between risk and return was not assessed in this study.
The example study used two most often employed risk analysis methods in process design decision making. Their simple application in this case and the fact that industry understands and believes in them supports their use. However, if the models become more complex and optimization is required for solving a part or the entire design problem, more advanced methods should be applied.

3. Conclusions

Methods for risk analysis for early stage biorefinery process design were reviewed and the particular sources of uncertainty for the FBR context were discussed.
Systematic accounting for all types of uncertainties is not common in early stage design; the simplest methods are employed for understanding better the impacts of variation in key input parameters of the models on economic performance of the alternatives. The results of the uncertainty analysis are not often used explicitly in decision making, but

rather they are presented and discussed to raise understanding. This potentially results in a subjective inclusion of risks in other decision making criteria. This subjectivity can be avoided by using risk analysis results systematically in decision making.

Acknowledgements

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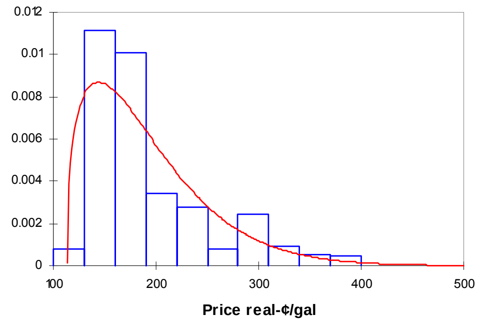
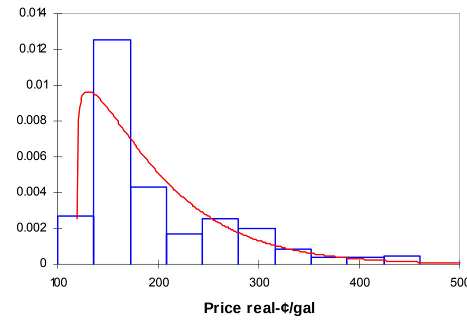
APPENDIX I – Probability distributions used in risk analysis



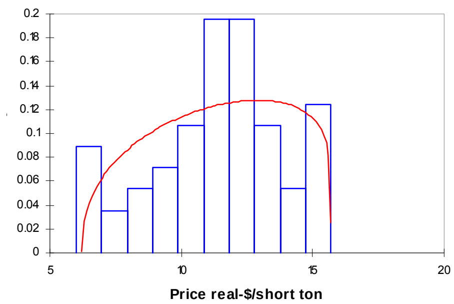
Historical retail gasoline real price (1993-2008) – Weibull distribution

(β = 1.336, γ = 0.846 and μ = 1.14 in \$/gal)[1]



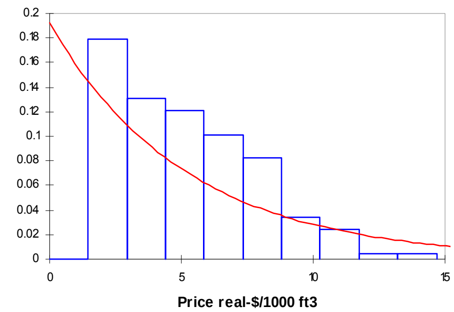
Historical retail diesel real price (1994-2008) – Weibull distribution

(β = 1.125, γ = 0.819 and μ = 1.19 in \$/gal)[1]



Historical lignite coal real price (1949-2007) – Beta distribution

(α = 1.422 β = 1.175, A = 6.216 and B = 15.703 in \$/short ton at mine)[2]



Historical natural gas real price (1997-2008) – Truncated exponential distribution

(λ = 0.192, min = 2.1 and max = 13.7 in \$/MMBTU) [3]

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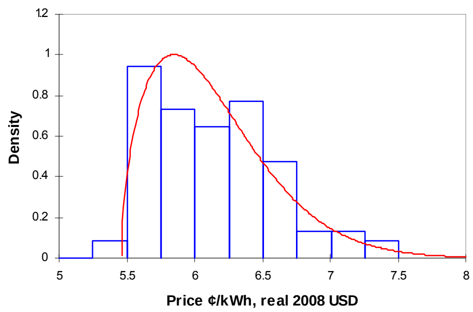
[1] U.S. Energy Information Administration. *Petroleum Navigator*. 2009 [cited 2009 September 2]; Available from: http://www.eia.doe.gov/

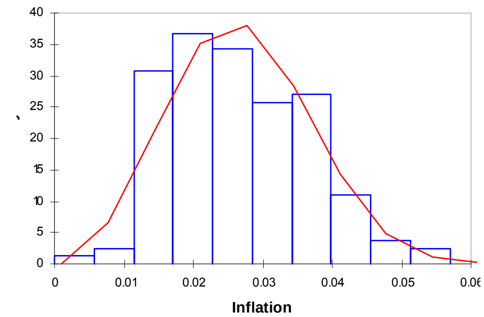
[2] http://www.econstats.com/spot/rt_coal.htm, http://www.eia.doe.gov/emeu/aer/txt/stb0708.xls

[3] U.S. Energy Information Administration. *Natural gas navigator*. 2009 [cited 2009 January 9]; Available from: http://www.eia.doe.gov/



Historical monthly industrial electricity price (2001 – 2008) – Weibull distribution

($\beta = 1.551$, $\gamma = 0.752$ and $\mu = 5.462$ in ¢/kWh)[4]



Historical inflation-% (1997-2008) – Weibull distribution

($\beta = 2.843$, $\gamma = 0.029$ and $\mu = 0.0009$)

Figure H.1 Price probability distributions based on historical data

Parameter abbreviations

A	Minimum in Beta distribution (four parameter notation)
B	Maximum in Beta distribution (four parameter notation)
α	Shape parameter of Beta distribution
β	Shape parameter of Weibull and Beta distributions
μ	Shift parameter of Weibull distribution
γ	Scale parameter of Weibull distribution
λ	Distribution parameter for Exponential distribution

[4] U.S. Energy Information Administration. *Wholesale electricity market data*. 2009 [cited 2009 September 2]; Available from: http://www.eia.doe.gov/

Table H.1 Price probability distributions estimated without historical tabulated data

Parameter	Standard deviation (%, Normal distribution)
Pulp	10 [5]
Raw materials	5

Table H.2 Annual inflation of costs (difference to normal inflation)

Parameter	Annual Inflation (%)	Trend standard deviation (%, Normal distribution)
Pulp	-0.5	0.5
Oil	2.0	1.0
Pulp wood	1.5	0.75
Forest residues & agro residues	2.5	1.25
Labour cost	0.25	-

[5] FOEX Indexes Ltd. *The PIX Pulp EUROPE Benchmark Indexes*. 2010 [cited 2010 June 10]; Available from: http://www.foex.fi/

APPENDIX J – Profitability probability distributions of traditional techno-economic analysis

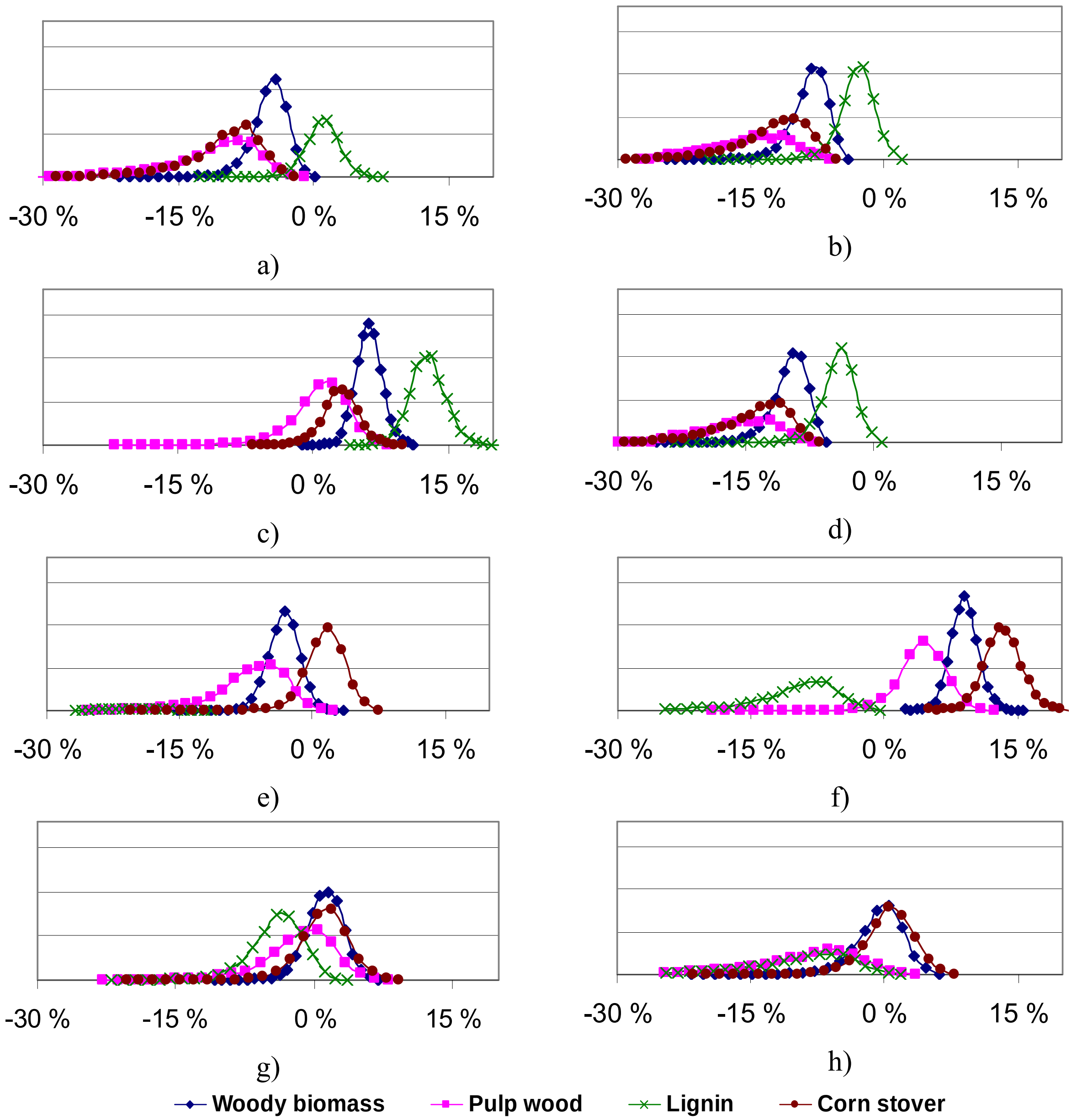


Figure J.1 Probability distribution of after-tax IRR of thermochemical biofuel production scenarios: a) Ethanol (gasification + MA synthesis), b) Ethanol (gasification + syngas fermentation), c) Ethanol (steam reforming + MA synthesis), d) Ethanol (steam reforming + syngas fermentation), e) MA (gasification + MA synthesis), f) MA (steam reforming + MA synthesis), g) FTL (gasification), and h) FTL (steam reforming)

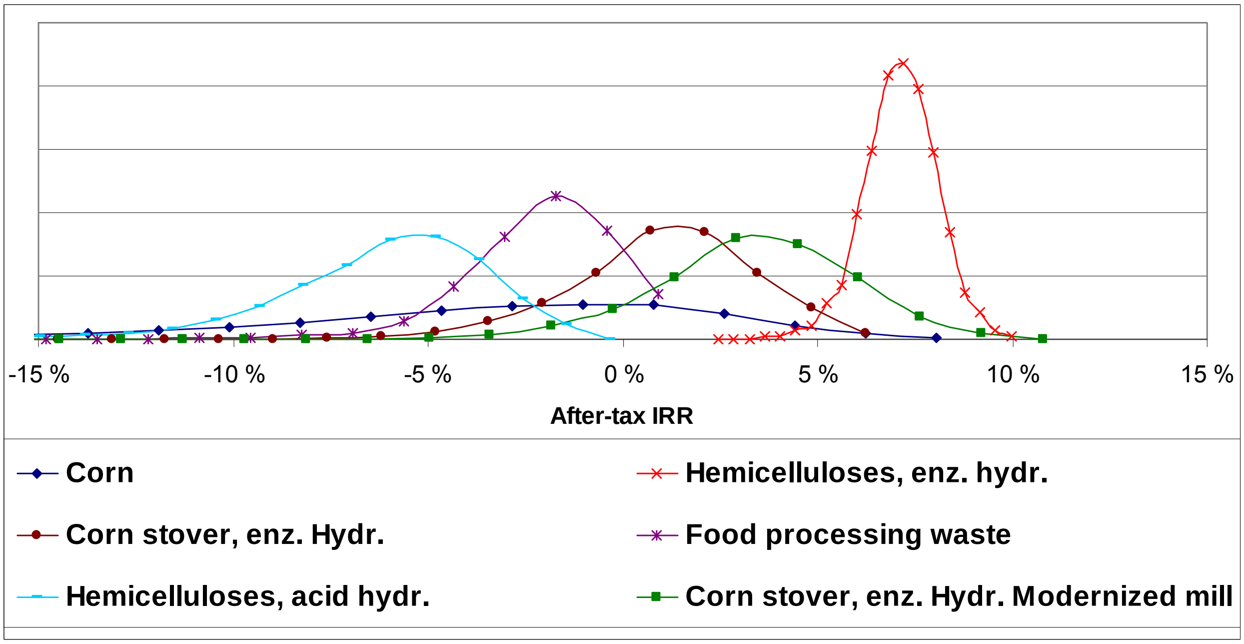


Figure J.2 Probability distribution of after-tax IRR of biochemical biofuel production scenarios

APPENDIX K – Definitions of MCDM criteria measures

Criterion 1 - Project profitability using after-tax internal rate of return (IRR)

$$NPV = \sum_{t=0}^{20} \frac{CF_t}{(1+IRR)^t} = 0 \qquad [K.1]$$

where NPV is net present value, t is time in years, CF_t is the cash flwo of year i.

Criterion 2 – Downside project profitability

$$IRR_{downside} = IRR_{\exp ected} - 1.96\sigma \qquad [K.2]$$

where σ is the standard deviation of IRR defined as

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \qquad [K.3]$$

Here n is the amount of measurements (iterations in stochastic modelling), x_i the IRR value of i:th iteration and μ the mean of IRR in all iterations.

Criterion 3 – core business benefit measured in the first year of full production after the retrofit

$$\Delta C = \Delta C_{pulp} + \Delta C_{paper} \qquad [K.4]$$

where ΔC is the change in production costs.

Criterion 4 – Feedstock paying capability is calculated using EBITDA (earnings before interest, taxes, depreciation and amortization) divided by the dry feedstock flow measured in the first year of full production after the retrofit. For projects using pulp wood (mill modernization, hemicellulose extraction prior to pulping) this is calculated for pulp wood. This

Criterion 5 – Capital efficiency measured in the first year of full production after the retrofit using return on capital employed (ROCE)

$$ROCE = \frac{EBIT}{Capital\ employed} \qquad [K.5]$$

where *EBIT* is earnings before interest and taxes and *Capital employed* the sum of book value of asset and working capital (inventories).

Criterion 6 - Share of revenues from new products from total revenues is measured in the first year of full production after the retrofit. Products that generate new revenues (including electricity which is not in base case produced in excess for sale) are considered.

Criterion 7 – Business risk is measured as the sum of free cash flows (FCF) from all operations (M$) until the first year of negative FCF. In addition, costs of mill closure are added to the total sum.